



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

DYNAMIC C2 DESIGN FOR ASYMMETRIC ADVANTAGE:

TEAMS OF AUTONOMOUS SYSTEMS AND PEOPLE

by

Dr. Mark E. Nissen

December 2017

Approved for public release; distribution is unlimited

Prepared for: Consortium for Robotics and Unmanned Systems Education and Research
(CRUSER)

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (DD-MM-YYYY) 12-30-2017		2. REPORT TYPE Technical Report		3. DATES COVERED (From-To) 10/01/2016 – 11/30/2017
4. TITLE AND SUBTITLE Dynamic C2 Design for Asymmetric Advantage: Teams of Autonomous Systems and People			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Dr. Mark E. Nissen			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Naval Postgraduate School			8. PERFORMING ORGANIZATION REPORT NUMBER NPS-IS-17-004	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT The technological capabilities of autonomous systems (AS) continue to accelerate, 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 through our recent research—representing the current state of the art—we have demonstrated computational experimentation capability in the TASP domain. We have also elucidated several technology trends indicating that unmanned aircraft may be diverging away from operating and behaving like their manned counterparts, even though phenomena such as swarming and mission integration appear to be upon us. This stream of research seeks to stay five to ten years ahead of practice, which enables us to anticipate both issues and opportunities in an area that remains under researched: C2 of autonomous systems. In this technical report, we build upon our computational experiments to address how TASP C2 can be designed for asymmetric advantage, with particular emphasis on dynamic design, through which an organization can increase agility and outperform otherwise peer or equivalent organizations.				
15. SUBJECT TERMS Artificial intelligence; autonomy; command & control; dynamics; design; experimentation; modeling & simulation; unmanned aircraft systems.				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 143
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		
			19a. NAME OF RESPONSIBLE PERSON Mark Nissen	
			19b. TELEPHONE NUMBER (include area code)	

THIS PAGE INTENTIONALLY LEFT BLANK

**NAVAL POSTGRADUATE SCHOOL
Monterey, California 93943-5000**

Ronald A. Route
President

Steven R. Lerman
Provost

The report entitled “Dynamic C2 Design for Asymmetric Advantage: Teams of Autonomous Systems and People” was prepared for and funded by Consortium for Robotics and unmanned Systems Education and Research (CRUSER).

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

This report was prepared by:

Dr. Mark E. Nissen
Professor

Reviewed by:

Dan Boger, Chairman
Information Sciences

Released by:

Jeffrey D. Paduan
Dean of Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The technologic capabilities of autonomous systems (AS) continue to accelerate, 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 through our recent research—representing the current state of the art—we have demonstrated computational experimentation capability in the TASP domain. We have also elucidated several technology trends indicating that unmanned aircraft may be diverging away from operating and behaving like their manned counterparts, even though phenomena such as swarming and mission integration appear to be upon us. This stream of research seeks to stay five to ten years ahead of practice, which enables us to anticipate both issues and opportunities in an area that remains under researched: C2 of autonomous systems. In this technical report, we build upon our computational experiments to address how TASP C2 can be designed for asymmetric advantage, with particular emphasis on dynamic design, through which an organization can increase agility and outperform otherwise peer or equivalent organizations.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION.....	1
A. AUTONOMOUS SYSTEMS	1
B. OPEN C2 QUESTIONS	2
C. COMPUTATIONAL EXPERIMENTATION.....	3
D. RESEARCH OVERVIEW.....	6
II. BACKGROUND	9
A. POWER COMPUTATIONAL ENVIRONMENT	9
B. POWER IMPLICATIONS	11
C. POWER MODEL EXAMPLE	13
D. NEXT GENERATION AUTONOMOUS SYSTEM FINDINGS.....	15
E. NEXT GENERATION AUTONOMOUS SYSTEM MODELS.....	17
1. Results from Previous Computational Experiments	17
2. Next Generation AS Analysis.....	21
III. RESEARCH METHOD	23
IV. RESULTS	25
A. RESULTS OVERVIEW.....	25
B. MULTIDIMENSIONAL C2 DESIGN VISUALIZATION AND ANALYSIS	25
C. C2 DESIGN ARCHETYPES	27
D. DYNAMIC C2 DESIGN.....	31
1. Overview	31
2. Conventional C2 Design Transition Rules and Guides	34
3. Unconventional C2 Design Transition Rules and Guides	38
V. CONCLUSION	43
VI. REFERENCES.....	47
VII. APPENDIX A.....	53
A. AIRCRAFT PERFORMANCE CHARACTERISTICS.....	54
B. MODEL TASK SPECIFICATIONS	55
C. MODEL STAFFING SPECIFICATIONS	56
D. BASELINE MODEL PARAMETERS	59
E. MODEL MANIPULATIONS.....	61
F. MODEL MEASURES	63
VIII. APPENDIX B	67
A. NUMERIC RESULTS.....	67
1. Duration	67
2. Rework.....	69
3. Coordination.....	70
4. Wait	71
5. Work Cost.....	72
6. Functional Risk	73

7.	Mission Risk	74
8.	Maximum Backlog.....	75
B.	GRAPHIC RESULTS	76
1.	Duration.....	76
2.	Rework.....	81
3.	Coordination.....	83
4.	Wait	84
5.	Work Cost.....	87
6.	Functional Risk	89
7.	Mission Risk	91
8.	Maximum Backlog.....	93
IX.	APPENDIX C	95
A.	METHOD SUMMARY	95
B.	COMPUTATIONAL EXPERIMENT DESIGN.....	96
1.	Autonomy.....	97
2.	Interdependence.....	100
3.	Experiment Conditions.....	102
C.	POWER SPECIFICATION AND TAILORING.....	103
D.	SUMMARY OF CONTROLS, MANIPULATIONS AND MEASURES....	104
1.	Controls.....	105
2.	Manipulations.....	106
3.	Measures	106
E.	POOLED INTERDEPENDENCE COMPUTATIONAL MODELS.....	106
1.	Baseline Model (D0P)	107
2.	D1P Model	113
3.	D2P Model	114
4.	D3P Model	115
5.	D4P Model	116
6.	D5P Model	117
F.	SEQUENTIAL INTERDEPENDENCE COMPUTATIONAL MODELS.	118
G.	RECIPROCAL INTERDEPENDENCE COMPUTATIONAL MODELS.	119
1.	D0R Model.....	119
2.	D1R Model.....	120
3.	D2R Model.....	121
4.	D3R Model.....	122
5.	D4R Model.....	123
6.	D5R Model.....	124
H.	INTEGRATED INTERDEPENDENCE COMPUTATIONAL MODELS.	125
1.	D0I Model	125
2.	D1I Model	126
3.	D2I Model	127
4.	D3I Model	128
5.	D4I Model	129
6.	D5I Model	130
	INITIAL DISTRIBUTION LIST	133

I. INTRODUCTION

A. AUTONOMOUS SYSTEMS

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

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

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 technologic sophistication continues to advance rapidly (e.g., in computational processing, collective sense making, intelligent decision making), a wide array of diverse robots (e.g., in hospitals; see Feil-Seifer & Mataric, 2005), unmanned vehicles (e.g., for highway driving; see Muller, 2012) and other intelligent systems (e.g., for industrial control; see McFarlane et al., 2003) continue to demonstrate unprecedented capabilities for extended, independent and even collective decision making and action

(e.g., offensive and defensive swarming; see Bamberger et al., 2006). Indeed, the technologic maturity of many AS available today (e.g., UCLASS – Unmanned Carrier-Launched Airborne Surveillance and Strike; see Dolgin et al., 1999) exceed the authority delegated to them by organizations and leaders; that is, their performance is limited more by policy than technology (e.g., see DoDD 3000.09, 2012).

In many skilled mission domains and under demanding environmental conditions (e.g., tactical surveillance; see Joyce, 2013), AS are replacing people at an increasing rate (e.g., unmanned vs. manned aircraft sorties; see Coutts, 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, ethics; see HRW, 2012). Task performance by AS is optimal in some situations, and performance by people is best in others, but in either case, the respective capabilities of autonomous machines and people remain complementary. As such, *integrated* performance, by complementary autonomous systems and people *working together*, can be superior in an increasing number of circumstances, including those requiring skillful collective action (Nissen & Place, 2013).

Hence there is more to this trend than simple technologic automation of skilled work by machines (e.g., 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, empiric evidence shows that AS can produce superior results—in some circumstances—when people are subordinate (e.g., see Bourne, 2013). This represents revolutionary change, and our

millennia of accumulated knowledge in terms of C2, organization, management, leadership, information science, computer science, human-systems integration and like domains leaves us largely unprepared to seize upon such situated performance superiority.

For another, under what circumstances should units comprised of people be organized, led and managed separately from counterparts comprised of AS (e.g., separate aircraft squadrons), and what circumstances favor instead organization integration¹ 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 underexplored 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, technologic capabilities, autonomy policies, personnel characteristics, skill levels and job types. Moreover, such computational experimentation and comparison can be accomplished very quickly and at extremely low cost relative to that required to experiment with teams or organizations in the laboratory—or especially in the field—with no risk of losing life, equipment or territory in the process (e.g., see Nissen & Buettner, 2004).

Toward this end, recent research (Nissen & Place, 2014)—representing the current state of the art (i.e., VDT; see Levitt et al., 1999)—has employed computational modeling and simulation technology to demonstrate computational experimentation capability in the TASP domain. Specifically, an agent-based model, which captures and reflects the structure, behavior and performance characteristics of C2 organizations in the field, is used to examine alternate C2 approaches and AS capabilities—both as available today and projected well into the future—in the context of exploring TASP opportunities, alternatives and decision spaces.

Computational models assess six distinct degrees of AS capability—ranging from *Degree 0 – no autonomy* (i.e., manned aircraft) to *Degree 5 – future capability* (e.g., AS matching or exceeding manned capabilities)—corresponding to both current and potential ship and aircraft platforms (i.e., CVN, DDG, LCS, F/A-18, MH-60, Scan Eagle, Fire Scout, Triton, Future AS). Models also assess four distinct levels of mission interdependence—ranging from *Pooled* (e.g., manned or unmanned missions in separate

airspace-times) to *Integrated* (e.g., manned *and* unmanned missions in common airspace-times)—as an orthogonal dimension. For instance, consider the nature of a mission—and its corresponding C2 requirements and complications—with an **unmanned wingman** flying alongside a manned aircraft leader, or symmetrically, consider a manned pilot flying as wingman alongside his or her unmanned aircraft leader.

Together these six degrees of autonomy and four levels of interdependence produce a 24 cell matrix of TASP contexts that are assessed in terms of C2 organization performance for a 24-hour ISR mission. Each cell is represented by a separate computational model, which is simulated 50 times, across eight performance dimensions, to create a substantial analytic space.

Further, we have assumed historically that next generation unmanned aircraft will operate and behave increasingly like manned aircraft. The problem is, several technology trends suggest that unmanned aircraft may be diverging instead of converging, developing their own, unique modes of operation and sets of behaviors. Indeed, other recent research (Place & Nissen, 2015) elucidates how some such modes and sets may make integration of manned and unmanned aircraft more challenging, not less, and we explore the next generation AS through six primary themes: 1) technology, 2) programmatic, 3) education and training, 4) culture, 5) operations, and 6) strategy.

Then we expand our recently enabled C2 computational modeling and simulation capability to address the properties and behaviors of such next generation unmanned aircraft systems, with particular emphasis on specifying even more advanced models for computational experimentation (Nissen & Place, 2016). This helps us to identify a number of novel C2 organizations and approaches (e.g., Collaborative, Edge) that offer considerable promise in terms of addressing next generation AS capabilities and trends, particularly as they pertain to themes such as education, training and culture.

Moreover, we may find ourselves soon in situations (e.g., seeking asymmetric advantage) that require *shifting dynamically from one C2 organization design and approach to another*. This is far beyond our current C2 capability but may be possible through dedicated research. This has enormous C2 implications.

D. RESEARCH OVERVIEW

This is where our ongoing research project continues to make an important contribution. This stream of research seeks to stay five to ten years ahead of practice, which enables us to anticipate both issues and opportunities in an area that remains under researched: C2 of autonomous systems (esp. unmanned vehicles, robots, Cyber applications). In great contrast with the huge effort expended to investigate the *technologic* characteristics, developments and advances of autonomous systems, a dearth of research addresses the corresponding C2. This is despite the quintessential importance of C2 and the fact that our current C2 strains under the load of having even two UAS, for instance, flying simultaneously in common airspace. Exacerbate such load with large numbers (e.g., swarms) of UAS, then exacerbate it further with missions that integrate manned and unmanned aircraft, and one realizes quickly that our contemporary C2 organizations and approaches are likely to fail in just a few years.

Yet swarms are taking to the air now, and on the near horizon are integrated manned-unmanned missions that can outperform those of either manned or unmanned alone. Indeed, an adversary with C2 capable of handling TASP missions can gain competitive advantage, even with autonomous systems that are technically inferior, and with C2 that increases organization agility, asymmetric advantage can be attained and possibly even sustained.

Through the research described in this technical report, we build upon our computational experiments to address how TASP C2 can be designed for asymmetric advantage, with particular emphasis on dynamic design, through which an organization can increase agility and outperform otherwise peer or equivalent organizations.

In particular, we employ our POWer computational experimentation environment to address the next generation battlespace, and we build upon our computational experiments to conceptualize dynamic C2 design in the TASP domain. Resulting insights enable us to characterize dynamic C2 design in terms of organizationally feasible archetypes and transitions, which in turn can inform situated Commander's intent and guide its subsequent timely staff and subordinate implementation, as a road map for advanced Fleet procedure, training and operations.

In the balance of this technical report, we first provide an overview of the POWer computational experimentation environment along with an example to help delineate computational modeling of C2 organizations and phenomena. Then we summarize the key findings from our research to understand and model next generation AS. We provide an overview of the research method subsequently, followed by key results, conclusions and our agenda for continued research along these lines.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

A. POWER COMPUTATIONAL ENVIRONMENT

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

This research stream continues today with the goal of developing new micro-organization theory and embedding it in software tools that can be used to design organizations in the same way that engineers design bridges, semiconductors or airplanes—through computational modeling, analysis and evaluation of multiple virtual prototypes. Such virtual prototypes also enable us to take great strides beyond relying upon the kinds of informal and ambiguous, natural-language descriptions that comprise the bulk of organization theory and 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 whole organizations—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 empiric 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 <i>driver</i> task) with another (called the <i>dependent</i> task). However, rework links also indicate that the dependent task depends on the success of the driver task, and that the project's success is also in some way dependent on this. If the driver fails, some rework time is added to all dependent tasks linked to the driver task by rework links. The volume of rework is then associated with the project error probability settings.
Task assignments	Show which actors are responsible for completing direct and indirect work resulting from a task.
Supervision links	Show which actors supervise which subordinates. In POWer, the supervision structure (also called the exception-handling hierarchy) represents a hierarchy of positions, defining who a subordinate would go to for information or to report an exception.

B. POWER IMPLICATIONS

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

The first is ontological: We model knowledge work through interactions of *tasks* to be performed, *actors* communicating with one another and performing tasks, and an *organization structure* that defines actors' roles and constrains their behaviors. Figure 1 illustrates this view of tasks, actors and organization structure. As suggested by the figure, the organization structure ontology is a network of reporting relations, which can capture micro-behaviors such as managerial attention, span of control and empowerment, and the task structure ontology is a network of activities, which can capture organization attributes such as expected duration, complexity and required skills. Within the organization structure, we further model various *roles* (e.g., marketing analyst, design

engineer, manager), which can capture organization attributes such as skills possessed, levels of experience and task familiarity. Within the task structure, we further model various sequencing constraints, interdependencies and quality/rework loops, which can capture considerable variety in terms of how knowledge work is organized and performed.

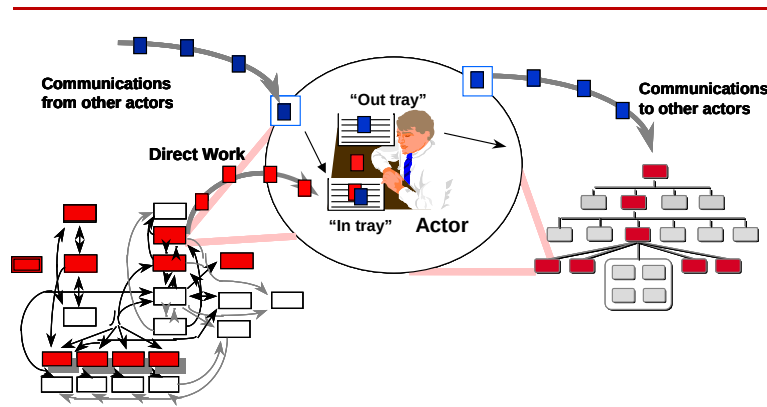


Figure 1 Information Processing View of Knowledge Work

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

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

The third implication is validation: The computational modeling environment has been validated extensively, over a period spanning roughly three decades, by a team of over 30 researchers (Levitt 2004). This validation process has involved three primary

streams of effort: 1) internal validation against micro-social science research findings and against observed micro-behaviors in real-world organizations, 2) external validation against the predictions of macro-theory and against the observed macro-experience of real-world organizations, and 3) model cross-docking experiments against the predictions of other computational models with the same input data sets (Levitt et al., 2005). As such, ours is one of the few, implemented, computational organization modeling environments that has been subjected to such a thorough, multi-method trajectory of validation.

C. POWER MODEL EXAMPLE

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

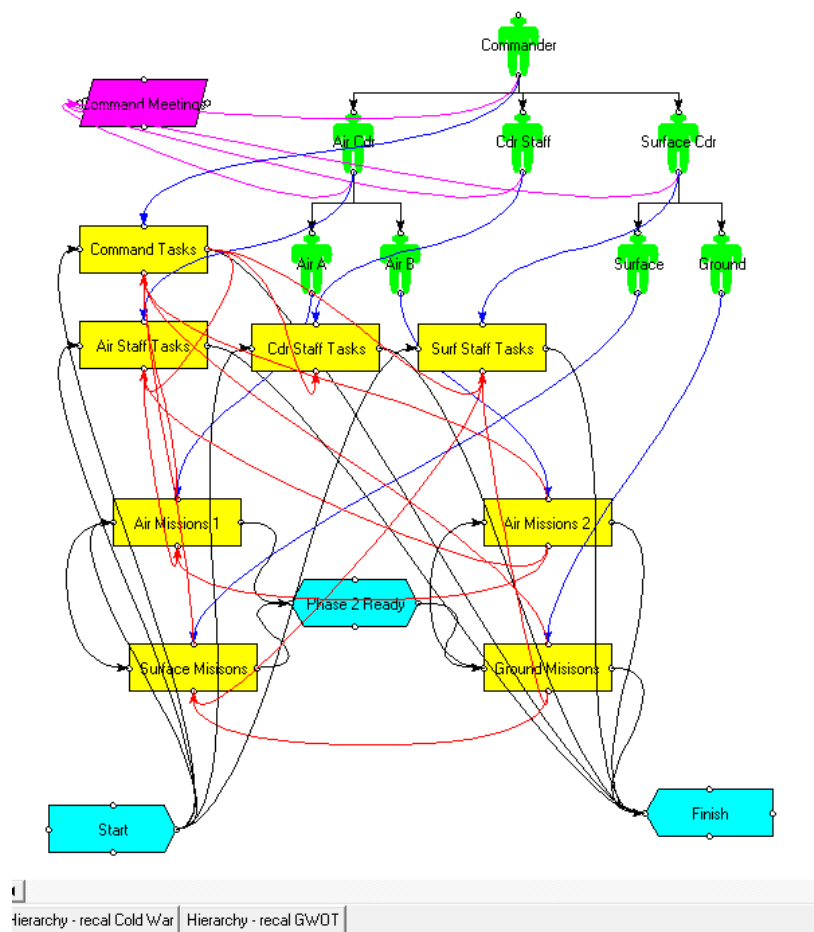


Figure 2 POWER Model Screenshot

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 looks somewhat different than the JTF representation depicted in the screenshot, and a major aspect of our modeling approach entails specifying 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.

D. NEXT GENERATION AUTONOMOUS SYSTEM FINDINGS

Here we summarize key findings from our recent research to understand next generation AS (Place & Nissen, 2015). In this relatively recent project we focus on expanding our C2 computational modeling and simulation capability to understand the next generation of unmanned aircraft systems, with particular emphasis on specifying even more advanced models for computational experimentation and the potential influence of Artificial Intelligence (AI).

In particular, we investigate technology trajectories and design visions for next generation unmanned aircraft systems through qualitative methods. Specific qualitative techniques include archival review, semi-structured interviews and participant observations. Qualitative data are collected, coded and analyzed continuously, with the data collection effort not stopping until theoretical saturation is reached. Coding adheres to well-accepted grounded theory building techniques, including the iterative open, axial and selective coding activities in series.

Key findings are organized into six primary themes that emerge from our coding and analysis of qualitative data: 1) technology, 2) programmatic, 3) education and training, 4) culture, 5) operations, and 6) strategy. Within the technology theme, we cite a number of examples and challenges for each driver, and we explain how they affect autonomy today as well as projecting how they portend to continue doing so in the future.

One major implication is that such complementary technologies combine to enable degrees of autonomy that far surpass systems in operation today. Another is that autonomous systems are becoming increasingly capable in their behavior, yet we find a diversity of technologic approaches to enabling such behavior. Traditional AI with its long and laborious knowledge acquisition process is giving way to machine learning techniques, and researchers are leveraging the human brain and biologic systems for technical insight, inspiration and architecture pertaining to autonomous thinking and learning. A third implication centers on computational hardware such as the memristor, which has biologic inspiration and enables new integrated capabilities, and the ever expanding requirement for UAS in particular to perceive their environments.

Within the programmatic theme, we note several reasons why autonomous capabilities remain slow in terms of reaching the field for operations. Such reasons center

on the software intensive nature of such capabilities and the challenges associated with software development and acquisition. We also note how numerous software developers in this area are not among the large DoD focused firms that build airplanes, ships and tanks; rather, many are comparatively very small firms, for which the DoD does not represent a major customer. Open systems architectures are very important too, and we note the challenges inherent in attempting to certify advanced autonomous systems, which cannot be tested exhaustively, particularly as they continue to learn and adapt after operational release and use.

The education and training theme emerges as a very important one, in which we highlight the importance of science, technology, engineering and math (STEM), particularly as it focuses on robotics and autonomy. Indeed, a focus on education and training may be as or more important than our current emphasis on technology.

Likewise with the culture theme, for the cultural acceptance of autonomy is clearly one of the most challenging issues. We have identified concerns with trust and ethics issues associated with the employment of unmanned systems. Such concerns point away from technology—although they have technologic underpinnings—yet are as or more important than the technology itself. What benefit can one expect from integrating manned and unmanned aircraft (e.g., in common squadrons, on common missions, through combined training exercises), for instance, if human pilots refuse to trust or even fly with their machine counterparts?

The greatest autonomy technology in the world will fail to support TASP if people cannot accept and learn to leverage it. Hence a very important research thrust emphasizes teaching autonomous systems how to interact with people as seamlessly as people (and AS) work with each other. We also note how public fear of armed autonomous systems has the potential to undermine even heroic technologic progress through the democratic voting system and civilian leadership of military organizations in the US.

Within the operations theme, we identify numerous operational needs for autonomy. Addressing current vulnerabilities in terms of interrupted communication represents one notable example, but leveraging the capabilities of computers that dominate human performance represents a critical example that undergirds TASP.

Reducing the manning levels required to operate UAS is clearly important too, where the mission manager approach could enable AS swarming and like behaviors.

Finally, the strategy theme provides an opportunity for us to summarize aspects of autonomy that are causing strategic disruption and need for change. Military leaders at the highest levels recognize the potential of AS in warfare and for deterrence alike, and the need for people and machines to work cooperatively together rises to the top of critical needs in this regard. We also note the potential for new arms races based on AS capabilities, and we emphasize the asymmetric nature of AS: The metaphoric price of entry into AS is relatively low.

E. NEXT GENERATION AUTONOMOUS SYSTEM MODELS

Here we summarize key findings from our recent research to model next generation AS (Nissen & Place, 2016). In this recent project we expand our C2 computational modeling and simulation capability to address the properties and behaviors of next generation unmanned aircraft systems, with particular emphasis on specifying even more advanced models for computational experimentation.

In particular, we analyze the technology trajectories and design visions for next generation unmanned aircraft systems and consider how to incorporate them into our POWER computational experimentation environment. Where necessary, we conduct computational experiments to reexamine the corresponding, updated TASP scenarios, which provide insights into why C2 breaks down and how to overcome its critical issues. Such insights enable us to anticipate key milestones in terms of C2 failure, and to lay out in advance the actions required to obviate such failure, as a road map for Fleet implementation.

First we summarize results from previous computational experiments. Then we analyze next generation AS capabilities for incorporation into the computational models and experiments.

1. Results from Previous Computational Experiments

Key findings pertain to our computational modeling and experimentation efforts, through which we develop and specify a set of computational models covering the whole matrix of 24 experiment conditions. The interested reader is directed to our prior work

(esp. Nissen & Place, 2014; Place & Nissen, 2015; Nissen & Place, 2016) for details regarding the research method, model specification, variable specification, experiment manipulations and controls, and like aspects of the research method. They could be repeated here for reference, but we choose to omit them from the body of this report for sake of brevity, focus and concision. Alternatively, we include such details as Appendix C.

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. Nonetheless, we keep the data presentation at a relatively high level, because we have so much data—through 36 different models, each simulated 50 times, across six autonomy degrees and four interdependence levels, assessed through eight performance dimensions—concise summarization is challenging.

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-time 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 airspace-times). 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 designing 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 knowledge 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.

2. Next Generation AS Analysis

This provides appropriate context for our work to analyze next generation AS capabilities for incorporation into the computational models and experiments, which we organize according to their six emergent themes: 1) technology, 2) programmatics, 3) education and training, 4) culture, 5) operations, and 6) strategy. Technology stands out as a powerful source of next generation AS capabilities and trends, with five major,

complementary, interrelated, technology drivers of increasing autonomy: artificial intelligence, machine learning, biologic design, computational hardware, and perception. In terms of interdependence, these technology drivers contribute principally toward supporting reciprocal and integrated missions and flight operations. Nonetheless, after thorough review and analysis, we do not see a compelling case for modifying our models to address this theme. Within the decade of future advances considered by the study—and reflected in the models—already, we have addressed such technology drivers well.

Likewise in terms of education and training or culture: Despite their importance, both have more to do with how we organize—with our approach to C2—than with next generation AS. We will address such important changes in future work that considers alternate C2 approaches, but we do not see a compelling case for modifying our models to address these themes either. Further so in terms of operations: We address the associated levels of autonomy and interdependence already, so we do not see a compelling case for modifying our models. Moreover with programmatic and strategy: Even our POWer model ontology is not equipped well to consider or react to these themes. Hence in the end, even after considering in detail our highly informative qualitative work to understand, accommodate and incorporate next generation AS, our original models prove to be quite robust.

III. RESEARCH METHOD

As noted above, the interested reader is directed to our prior work (esp. Nissen & Place, 2014; Place & Nissen, 2015; Nissen & Place, 2016) for details regarding the research method, model specification, variable specification, experiment manipulations and controls, and like aspects of the research method. They could be repeated here in the body of this technical report for reference, but we choose to omit them from the body of this report for sake of brevity, focus and concision. Alternatively, we do include such details as Appendix C, which follows the detailed Appendices A and B for reference. Together, for they provide an abundance of important information without distracting from the focus of this current project.

In this focused study, we build upon results of computational experimentation to conduct this research project, and we leverage advanced theory and application that integrates C2 with Organization and Management Theory (OMT) to conceptualize dynamic C2 design in terms design archetypes, C2 maturity, and organizationally feasible transitions. This research is principally analytic in nature, centering on mapping concepts and techniques from organization design to consider the dynamics of design in the C2 domain.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. RESULTS

A. RESULTS OVERVIEW

In this section we present the key findings and results of our current research. Building upon the background research summarized above, we address dynamic C2 design. This begins with articulation of a multidimensional approach space for visualizing and analyzing different C2 designs. The discussion continues with conceptualization of five C2 design archetypes, which we follow by addressing dynamic C2 design directly.

B. MULTIDIMENSIONAL C2 DESIGN VISUALIZATION AND ANALYSIS

Drawing heavily from Alberts and Nissen (2009), we articulate a multidimensional approach space for visualizing and analyzing different C2 designs. By *approach space*, we also mean *design space*, and we use the terms *C2 approach* and *C2 design* interchangeably; that is, a C2 approach reflects a C2 design, whether such design is explicit or implicit (e.g., designed purposefully or reflecting practical default).

The three dimensional approach space depicted in Figure 3 can be used to describe a wide variety of C2 designs (e.g., different approaches to accomplishing the functions associated with C2 for a diverse set of teams, organizations or collectives). The three dimensions that form the C2 Approach Space are depicted graphically as orthogonal.

The Allocation of Decision Rights (ADR) dimension can be considered from either the perspective of a single organization (e.g., command, ship, fleet) or a collection of entities (e.g., joint task force, coalition task force, humanitarian or disaster relief effort). Clearly the distinction between a single organization and collection of entities is not sharp (e.g., even a single organization such as a command represents a collection of entities such as departments, divisions and branches), but it is useful to understand the breadth of application to multiple organizations banding together (even loosely) toward some (even only partially) shared objectives.

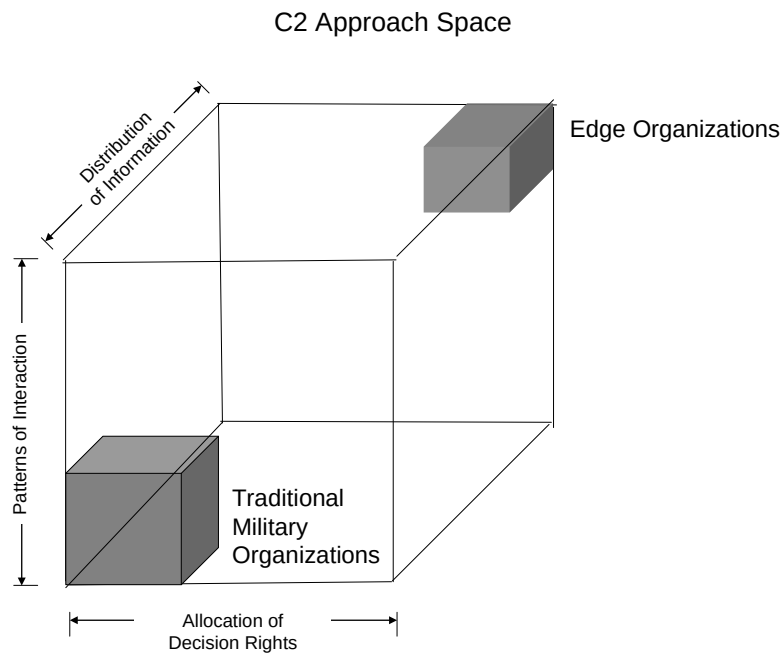


Figure 3 C2 Approach Space (Adapted from Alberts & Nissen, 2009)

The end points of ADR are “none” and “broad,” indicating no delegations of authority and, respectively, complete authority delegation. The Patterns of Interaction (PoI) dimension spans a continuum from “highly constrained” to “unconstrained,” while the Distribution of Information (DoI) dimension spans a spectrum from “none” to “broad.”

Theoretically the three dimensions are independent and orthogonal, but practically the design settings of one tend to influence the settings of others. The closer to “none” that a C2 design falls on the ADR scale (i.e., left part of the approach space), for instance, the greater the likelihood that PoI and DoI will cluster together toward “highly constrained” (i.e., lower part of the approach space) and “none” (i.e., front part of the approach space), respectively, in practice.

Such clustering is depicted in Figure 3, where the left-lower-front area of the approach space reflects a C2 design point that represents the traditional military organization. Quite typically, most military organizations concentrate power and authority in their commanders (i.e., ADR is very limited); organization departments, divisions and branches are divided vertically and do not interact extensively (i.e., PoI is

very constrained); and information flows vertically along highly centralized communication channels (i.e., DoI is very narrow).

Although traditional, clearly this is not the only way to design C2 for a military organization. Indeed, theoretically any point within the C2 design space can be used to do so. In practice, however, C2 designs tend to cluster at specific design points where the three dimensions cohere together and complement one another. As a contrasting instance, notice the design point in Figure 3 labeled “Edge Organizations” at the right-upper-rear corner of the approach space. This delineates broad ADR (e.g., extensive delegation of authority), unconstrained PoI (e.g., various organization departments, divisions and branches interact horizontally across boundaries), and broad DoI (e.g., information is shared freely across the organization).

Notice this reflects a C2 design point representing an approach that is dramatically different than the traditional military organization discussed and delineated above. Nonetheless, the Edge C2 design can prosper in situations where the traditional military organization struggles, and vice versa (Gateau et al., 2007). Further, as noted in our previous research, there is no single C2 design that is most appropriate for all missions and environments at all times (Nissen & Place 2016), and many different C2 design points can be achieved by any particular organization (Alberts & Nissen, 2009). Indeed, each point is unique, but several C2 design points are prominent and revelatory.

C. C2 DESIGN ARCHETYPES

Continuing to draw from Alberts and Nissen (2009), in this section we conceptualize five C2 design archetypes, and we use the approach space for their visualization and analysis. Each archetype corresponds to a particular design point, which we conceptualize by changing all three approach space variables (i.e., we alter ADR, PoI and DoI). These five archetypes are called: 1) Conflicted C2, 2) Deconflicted C2, 3) Coordinated C2, 4) Collaborative C2 and 5) Edge C2. Each is unique theoretically and can be related to a C2 design point in practice. As a set they comprise a useful and distinct collection of reference points.

Figure 4 depicts how these archetypical C2 designs are mapped to each axis of the approach space. Note that the boundaries between C2 designs depicted in this figure (e.g.,

the place where Deconflicted becomes Coordinated) are fuzzy and not delineated sharply. We use this graphic device to convey approximate relations between the C2 design points and dimensional axes, so as not to imply precise definition or operationalization.

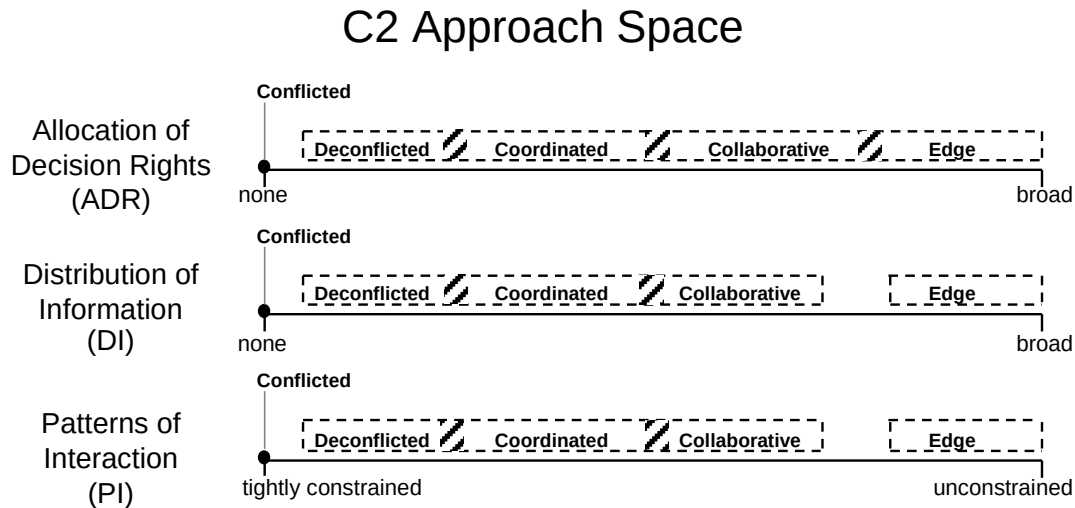


Figure 4 C2 Approach Space Dimensions (adapted from Alberts & Nissen, 2009)

Figure 5 plots the five archetypal C2 designs according to the three axes depicted above. Point A corresponds to Conflicted C2 and occupies an extreme point on the left-lower-front corner of the space (i.e., no allocation of decision rights, completely constrained patterns of interaction, no distribution of information). Another way to think about the Conflicted design point is in situations where there is no deliberate C2: No one person or organization is leading, organizing and managing, and the various participants are in conflict in terms of their individual goals and activities. Although such an extreme C2 design is unwelcome in practice (esp. because conflict impedes organization efficacy), this archetype represents an important theoretic design point for comparison with others. It also represents an important practical design point in terms of transition, which we address via dynamic C2 design below.

The Deconflicted C2 archetype is plotted very near its Conflicted counterpart, but it is not situated on Point A exactly: Although it is plotted very near the vertex, this design point reflects some distance from the corner point in terms of ADR, PoI and DoI.

Nonetheless, decision making is kept very centralized, patterns of interaction reflect minimal overlap, and information is distributed, but the organization is able to keep its people and process out of conflict with one another. One can think of this as the minimal level of C2 for efficacy, which sets it apart practically from its Conflicted counterpart. Further, although this design point is theoretic, notice how it maps closely to the traditional military organization described and delineated above. We return to such mapping below.

With respect to the Deconflicted design point, the Coordinated C2 archetype is delineated still further away from Point A along all three dimensional axes. Hence it reflects broader ADR, less constrained PoI, and more expansive DoI than either its Conflicted or Deconflicted counterparts. As such, this third archetypical C2 design incorporates more delegation of authority, more cross-functional interaction, and more information sharing than the others. In addition to enabling the organization to resolve conflicts, its various participants are also able to coordinate their activities, which set it apart practically from its Deconflicted counterpart.

The Collaborative C2 archetype is delineated still further away from Point A than the Coordinated design. Hence it reflects even broader ADR, even less constrained PoI, and even more expansive DoI than its Conflicted, Deconflicted and Coordinated counterparts. As such, this C2 design incorporates abundant delegation of authority, extensive cross-functional interaction, and pervasive information sharing. In addition to enabling the organization to resolve conflicts, and in addition to enabling various organization participants to coordinate their activities, they can plan, interact and operate collaboratively, which sets it apart practically from its Coordinated counterpart.

Finally, the Edge C2 archetype is delineated at the opposite corner from Point A (i.e., near Point H). Hence it reflects complete ADR, unconstrained PoI, and unlimited DoI. As such, this C2 design reflects a meritocracy, in which leaders emerge and subside on occasion as conditions require; organization boundaries such as departments, divisions and branches cease to exist; and all information is available to all organization participants at all times. This set of conditions sets the Edge C2 design point apart theoretically and practically from all of its counterpart archetypes. Clearly it reflects an extreme approach to C2.

C2 Approach Space

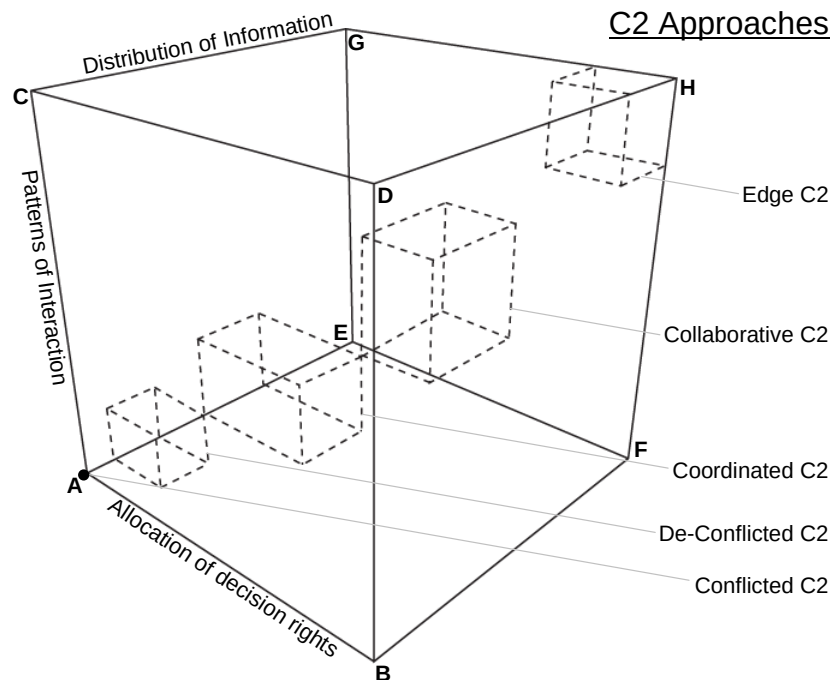


Figure 5 C2 Approach Space (Adapted from Alberts & Nissen, 2009)

Notice the C2 design archetypes depicted in the figure appear to progress along a rough diagonal from Point A to Point H; that is, as the C2 design progresses from Conflicted through Deconflicted, Coordinated and Collaborative to Edge C2, their corresponding positions in the C2 Approach Space shift, almost linearly, from the left-bottom-front to the right-top-rear corners of the space. Theoretically we can conceptualize myriad design points that lie off of this rough diagonal, but in practice C2 designs tend to cluster along it, and they tend to mirror one or more of the five archetypes delineated in the figure.

The reader will note that each C2 design archetype delineated in Figure 5 is represented as a rectangular region with the C2 design space. Although we refer to each archetype in terms of a “design point,” we allow for the possibility that numerous, highly homogeneous yet somewhat distinct, specific C2 design points will cluster within—and hence instantiate—each archetype. This also makes sense in practice, as many

organizations may pursue and implement C2 designs that are highly similar yet not exact replicas.

The ability of an organization or a collective to move through the C2 Approach Space is related to the concept *C2 maturity* (SAS-065, 2008). The more capable that an organization becomes in terms of C2, the farther away from Point A it is able to operate, and the more challenging mission-environment conditions it can handle effectively. Of course, increased maturity comes at a cost. Not only must an organization expend considerable time and energy to transition from one maturity level to another, but speaking generally, the higher the C2 design, the greater the coordination effort required.

Further, as an organization becomes capable of operating farther and farther along this diagonal, it develops the ability to function effectively across a larger volume of the C2 Space. For instance, an organization capable of Coordinated C2 could also implement Deconflicted C2 if it chooses to; likewise, an organization capable of Collaborative C2 could also implement Coordinated or Deconflicted, and an organization capable of Edge C2 could implement any approach. The interested reader is referred to (SAS-065, 2008) for details. We say more about both maturity levels and transitions in the following section.

D. DYNAMIC C2 DESIGN

In this section we discuss dynamic C2 design in some detail. We begin with an overview that includes a practical illustration. We follow this with rules and guides for transition from one conventional C2 design to another, and we include an illustration pertaining to dynamic C2 design in an unmanned aircraft context within the US Navy. Then we outline a set of rules and guides for transition from one unconventional C2 design to another, which includes a disaster relief illustration.

1. Overview

The term *dynamic* connotes change through time, whereas its counterpart *static* connotes temporal stability. When we consider C2 design as above, we speak principally about static design; that is, we design C2 for an organization via dimensional settings such as ADR, PoI and DoI, and we expect for such organization to operate accordingly

for a long time, if not forever. Take the traditional military organization discussed above, for instance: The narrow ADR, constrained PoI and limited DoI have represented quintessential aspects of C2 since the dawn of military organization. Hence the corresponding C2 design is static.

However, as noted above, no single C2 design is most appropriate for all missions and environments at all times. Consider a multinational disaster relief effort, for instance, such as the response to the tsunami, generated by a magnitude 9.2 offshore earthquake, that struck Indonesia in 2004. In response to the devastation, over 3500 NGOs (non-government organizations) came to help the many thousands of Indonesian people who were without food, water, shelter or power (SAS065, 2008).

The Indonesian Government had lost nearly all of its C2 capability, and it was clearly not in charge of the relief effort. Neither was the US Military, which had a presence in Banda Aceh along with units of several other nations' militaries, nor was any one of the NGOs in charge. Quite the opposite: No one was in charge, and each individual organization was pursuing its own goals and activities independently, even while conflicting with those of other organizations (e.g., with multiple doctors or other relief workers converging redundantly on the same village, while other villages were left unattended).

Each *individual* organization was operating in the context of its *particular* C2 approach (e.g., the Indonesian Government reflected Conflicted C2; the US Military organization reflected Deconflicted C2; Doctors without Borders reflected Coordinated C2), but the overall relief effort—associated with the *collective* of such individual organizations—reflected *Conflicted* C2: No one was in charge of the collective as a whole, and many of the goals and activities of such collective were in conflict, with no C2 in place collective-wide to resolve the conflicts.

This represents a situation in which the traditional military approach to C2 (i.e., Deconfliction) may not serve the mission best—or even be feasible—because this approach requires someone to be in charge, or if no one is in charge, then all of the participants must at least agree on a common deconfliction plan. Deconflicted C2 represents higher maturity than the Conflicted approach, hence it would enable the relief effort to handle the associated chaos better and at least be somewhat effective. Had the

Indonesian Government, for instance, been able to reestablish itself as an authority and resource capable of planning, directing and participating in the relief effort, then it might have been able to establish a Deconflicted C2 approach, and as the sovereign, the various military units and NGOs would have been obliged to agree and adhere to its approach. The government was unable to do so, however.

Alternatively, were the US Military, as another instance, to attempt taking charge and leading the relief effort in its entirety, then it would most likely have failed also: Very few if any NGOs feel compelled to listen to—much less take orders from—a military organization. The US Military certainly had established Deconflicted C2 *for its own organization*, but it would have been quite a challenge to impose such C2 on the rest of the relief collective.

Perhaps the US and other participating nations' military units could have agreed upon a common deconfliction approach (e.g., based on geography), and hence achieved Deconflicted C2 *for the military units*, but unless the NGOs were part of the discussion and agreement, then only the military part of the relief effort would have reflected Deconflicted C2, with the remaining majority of organizations in the collective centered on Conflicted C2 still.

Hence although Deconflicted C2 makes sense (e.g., due to higher maturity) and is possible in theory, in practice such C2 design would likely be infeasible for a large collective such as this, particularly in transition from its Conflicted state. In contrast, given its wide open and unconstrained nature, an alternate C2 approach such as the Edge, which reflects the highest maturity, may fit considerably better, because leadership is emergent, situated and ephemeral, for instance.

Thus, we see a need for transition from one C2 design or approach to another, yet not all transitions appear feasible in practice (e.g., Conflicted to Deconflicted seems infeasible for an ad-hoc collective). Clearly this represents an unconventional and extreme case illustration, but it elucidates well the underlying need for dynamic C2 design. Even more conventional and common cases, such as military organizations from different nations adjusting their C2 for coalition operations, for instance, can necessitate dynamic C2 design.

Concisely, the idea of dynamic C2 design is for an organization to shift from one C2 approach to another—perhaps even temporarily, in response to a natural disaster, for instance—as diverse missions and environments necessitate. Drawing from our C2 approach space and archetypes, a first step toward such dynamic design is to recognize the five different C2 design archetypes, to understand the mission-environment conditions in which each fits best, and to learn how an organization can shift back and forth between them. Indeed, as our disaster relief example elucidates, in something of a Markov sense, an organization’s current C2 design appears to constrain which alternate designs are possible in terms of transition.

This varies a bit depending upon whether an organization is engaged in conventional versus unconventional C2 designs and transitions. For purposes of this discussion, three C2 design archetypes are included in the conventional category: Deconflicted, Coordinated and Collaborative. This is because each of these designs is comparatively common and familiar to organization theorists and leaders, and because the transitions between them are relatively straightforward and linear. The two unconventional archetypes are Conflicted and Edge. These are less common and familiar, and the transitions are comparatively complex. We begin with the conventional.

2. Conventional C2 Design Transition Rules and Guides

Drawing further from theory (Alberts & Nissen, 2009), once an organization has established Deconflicted C2, then it can progress incrementally along the rough diagonal (e.g., increasing maturity levels) noted above in terms of the C2 design space. For several instances, it can broaden ADR, loosen PoI constraints, and expand DoI to transition from Deconflicted to Coordinated C2; after which it could further broaden, loosen and expand to transition from Coordinated to Collaborative C2. These represent logical and incremental transitions.

In theory, the organization could continue its broadening, loosening and expanding to reach the Edge C2 design point, and then transition back through one or more of these other archetypical C2 design points to reach Deconflicted again. Likewise, in theory, the organization could (not that it would want to) transition down to Conflicted and back. In practice, however, as noted above, these last two transitions would be highly unconventional.

If we assign Roman numerals to the five archetypical C2 design points (i.e., I – Conflicted, II – Deconflicted, III – Coordinated, IV – Collaborative, V – Edge), then we can depict the transition paths outlined above as follows:

(1) $I \rightarrow II \rightarrow III \rightarrow IV \rightarrow V$

(2) $V \rightarrow IV \rightarrow III \rightarrow II \rightarrow I$

Path (1) depicts the transition from Conflicted all the way to Edge, and Path (2) depicts the reverse transition from Edge all the way back to Conflicted. As noted above, however, both such complete paths are possible in theory but challenging in practice. Focusing instead on the conventional C2 design points and transition, we shorten the paths by truncating both end points (i.e., I, V) to depict Paths (3) and (4).

(3) $II \rightarrow III \rightarrow IV$

(4) $IV \rightarrow III \rightarrow II$

Moreover, if both of these conventional paths are possible and feasible in total, then any of the constituent subpaths (i.e., $II \rightarrow III$, $III \rightarrow IV$, $IV \rightarrow III$, $III \rightarrow II$) are too. Hence we have outlined the set of four feasible, conventional transitions.

Theory suggests further that an organization cannot skip transition steps along these paths, for the distance (e.g., consider the degree of organization change required and disruption experienced) is too great. For instance, the transitions $II \rightarrow III$ and $III \rightarrow IV$ are feasible, as are their reverse transitions, but $II \rightarrow IV$ and $IV \rightarrow II$ are not, because they skip a step. Thus, if an organization finds itself at a design point of Deconflicted C2, for instance, and it desires to transition to a higher design (e.g., Collaborative), then its first transition must necessarily be to Coordinated (i.e., $II \rightarrow III$). Now we're able to plan dynamic C2 design in terms of three steps:

Step 1. Observe your current C2 design point (C2c).

Step 2. Identify your desired C2 design point (C2d).

Step 3. Transition incrementally from C2c <through C2n> to C2d.

The first step is to fix an organization's current C2 design point (e.g., Deconflicted). The second is to identify its desired design (Collaborative). The third is to transition through one or more incremental steps (e.g., $II \rightarrow III$, $III \rightarrow IV$) from the current to the desired design point.

For illustration, say that a US Military organization (e.g., a CTG) reflects Deconflicted C2 in terms of UAS operations at sea. As noted in prior research (Nissen & Place, 2016), this suggests that no two UASs can operate in the same airspace at the same time (i.e., the C2 deconflicts airspace-time). Likewise, as such, no UASs may operate in the same airspace-time as manned aircraft. Say, however, that a new mission requires contemporaneous airspace operations (e.g., multiple unmanned and manned aircraft flying together), and the military organization must increase its maturity and transition to a higher C2 design (e.g., Coordinated or Collaborative). We can follow the steps above, and utilize our transition map, to assist the Commander in expressing intent and to guide the Commander's staff and subordinate leaders in satisfying such intent.

The intent could read, for example, something like, "We need to transition our UAS operations at sea from Deconflicted C2 to Collaborative C2 (within X time period) in order to complete Mission Y." The Commander's staff could then identify the required transition path (i.e., II $\rightarrow$ III, then III $\rightarrow$ IV), and they could in turn develop guidelines for subordinate commanders, for example, as something like, "We need to delegate authority (i.e., broaden ADR), loosen constraints across ships and departments (i.e., increase PoI), and expand information sharing across units (i.e., broaden DoI)." It would then be up to subordinate leaders to determine exactly how to do so in a manner that makes the most sense in terms of the organization and its mission.

In terms of the contemporaneous aircraft operations noted above, consider even the simple case of two *manned* aircraft being flown *from different ships*. For instance, say that two MH-60s are to cooperate on a mission but that each helo is from a different ship (e.g., one from a DDG, another from an LCS). Under most current C2 rules (e.g., Deconflicted C2), the lowest level person with authority over both aircraft is the CTG, which represents a very high level officer to oversee two helos in flight. A higher maturity C2 design (e.g., Coordinated) would likely be more appropriate and provide a better fit.

Moreover, say further that the two MH-60s from above were to also fly with *unmanned* aircraft (e.g., two FireScouts). This integration of manned and unmanned aircraft operations would bring additional organizations and personnel (esp. associated

with unmanned aircraft) into the C2 design, which would likely require a further maturity increase (e.g., transition to Collaborative C2).

Recall, however, that only one transition at a time is permitted (e.g., Deconflicted to Coordinated, Coordinated to Collaborative). Thus, the CTG would be wise in calling for such dynamic C2 transition in two steps: Perhaps the two MH-60s from different ships could fly together first, giving the organization time to work through and learn from the first C2 transition (i.e., II → III: Deconflicted to Coordinated), after which they could learn to fly with the FireScouts, as the organization transitions further (i.e., III → IV: Coordinated to Collaborative).

The first transition from Deconflicted to Coordinated, for instance, could begin with an ADR adjustment along the lines of delegating such authority over the MH-60s from the CTG to the Captain of one ship or the other. Notice that such ADR adjustment could be limited in scope (e.g., concerning only the two MH-60s on that mission) and ephemeral (e.g., only until the mission is complete). Thus, we see how a C2 design need not be ubiquitous, monolithic and permanent (e.g., one design for the whole organization, always). Rather, some aspects of C2 can reflect one design point (e.g., Coordinated C2 for the MH-60 mission), whereas most if not all others can reflect a different one (e.g., Deconflicted for everything else).

Consider further the patterns of interaction. In Deconflicted C2, the organizations associated with the two MH-60s (e.g., one on the DDG, another on the LCS, flying in separate airspaces) would have little interaction with one another. In a transition to Coordinated C2 for the contemporaneous MH-60 mission, however, the organizations would need to interact, for their aircraft would be sharing airspace-time. This represents a loosening of PoI. Likewise, the two ships and organizations might initially have minimal information sharing on independent helo flight operations, but the transition to Coordinated C2 for the MH-60 mission would likely require broader distribution of information across the ships and associated organizations.

Undertaking the subsequent transition from Coordinated to Collaborative C2 would require additional steps. For instance, the organization could pursue even more delegation (i.e., broader ADR)—perhaps from the Captain of one ship to his or her Operations Officer—even more interaction across organizations (i.e., expanded PoI)—

perhaps synchronous VTC, radio and or chat conversations across aircraft operations personnel on both ships—and even greater information sharing between organizations (i.e., wider DoI)—perhaps posting all associated information on a common SharePoint, CAS or like site accessible to participants on both ships.

Such C2 transitions may not be required, however, as the CTG could choose instead to retain authority and centralize information (i.e., limit ADR and DoI), for instance by assigning staff members to oversee the ships' air operations (e.g., via a Joint Air Operations Center). Even so, the patterns of interaction between ships would necessarily increase through contemporaneous airspace operations (i.e., greater PoI), and the resulting CTG C2 design point would not correspond with one of the five archetypes. Specifically, with narrow ADR and DoI but less constrained PoI, the C2 design point would definitely be off of the rough diagonal described in terms of the approach space, with a C2 design that is comparatively incoherent.

What began as theory comes now to practice. With a realistic, contemporary scenario suggesting a transition to higher maturity C2 at sea, not only do we have theory to guide such transition, we also have a set of concrete and discrete steps to effect it. Moreover, in addition to documenting the theory and corresponding practice through this technical report, the associated new knowledge represents something that can be taught in military schools, formulated through standard operating procedures (SOPs), along with techniques, tactics and procedures (TTPs), and practiced through training exercises. A considerable step forward in terms of C2!

3. Unconventional C2 Design Transition Rules and Guides

Now we address the unconventional C2 design transition rules and guides. As noted above, such unconventional transitions involve the Conflicted and Edge C2 archetypical design points. It is difficult to understand, for instance, why any organization would ever wish to transition to a Conflicted design, and it is challenging for any organization to transition to an Edge. However, as discussed in the tsunami illustration, an organization or collective may find itself in a Conflicted design through default, and it would likely wish to increase maturity and transition to some other, higher design point. Likewise, an organization may find itself in an Edge design through great effort, but it may wish to transition to a lower design point to ease coordination efforts. As noted

above, speaking generally, the higher the C2 design, the greater the coordination effort required. We examine both of these design points.

In the first, where an organization or collective finds itself in Conflicted design, our transition rules point toward two alternate paths. In the one noted but largely dismissed in the tsunami illustration, the path $I \rightarrow II$ (i.e., Conflicted to Deconflicted) is possible theoretically but seemingly infeasible in practice. This is because some organization must be in charge to impose and achieve the deconfliction, or all participating organizations must agree to a common deconfliction approach. In the case of an incapable sovereign and a plethora of NGOs, even if the participating military organizations, for instance, could establish geographic or like deconfliction boundaries for themselves, only the military part of the collective would reflect Deconflicted C2, with the majority of other organizations operating via Conflicted C2 still.

Alternatively, the (collective) organization could attempt the unconventional transition $I \rightarrow V$ (i.e., Conflicted to Edge). This may appear on the surface to violate the incremental rule set forth above (i.e., taking only one transition step at a time), for the Edge is depicted symbolically as four transition steps above Conflicted C2. However, we allow for transitions both up and down the path. Hence we can combine Paths (1) and (2) to delineate bidirectional transitions as shown in Path (5):

$$(5) I \leftrightarrow II \leftrightarrow III \leftrightarrow IV \leftrightarrow V$$

Moreover, if we view both ends of this bidirectional path as linked, as opposed to opposite endpoints along a line, then the $I \rightarrow V$ transition begins to look possible. We delineate such linked transitions in Figure 6. On the right side, we show the three conventional C2 design points and transitions (i.e., $II \leftrightarrow III \leftrightarrow IV$), and we illustrate their interrelationship as being relatively close to one another to indicate that transitions between them are comparatively easy for an organization. We also position these three points somewhat hierarchically to indicate that each represents a higher C2 design—and hence reflects greater maturity—than the one below (i.e., $IV > III > II$).

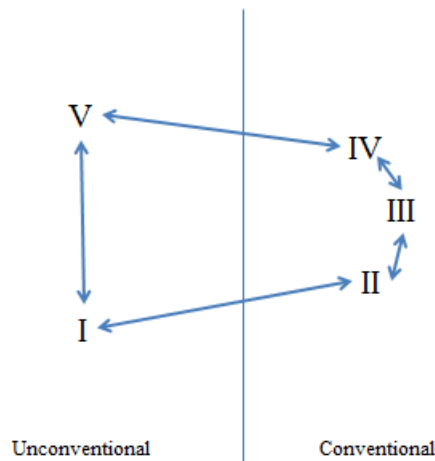


Figure 6 Linked Transitions

On the left side of the figure, we show the two unconventional C2 design points and transitions (i.e., $I \leftrightarrow V$), and we illustrate their interrelationship as being relatively far from one another to indicate that transitions between them are relatively difficult for an organization. We also position these two points hierarchically to indicate that one represents a higher C2 design—and hence reflects greater maturity—than the other (i.e., $V > I$).

Further, we position the conventional C2 archetypes comparatively far from both of their unconventional counterparts to show the great difficulty associated with the corresponding transitions (i.e., $I \leftrightarrow II$, $IV \leftrightarrow V$). Although it may be difficult to discern in the figure, however, the transition distance between the two unconventional design points (i.e., $I \leftrightarrow V$) is less than that between either unconventional-conventional counterpart (i.e., $I \leftrightarrow II$, $IV \leftrightarrow V$). This indicates that the difficulty of transitioning between the two unconventional design points is less than transitioning between unconventional and conventional. Hence the transition $I \leftrightarrow V$ may be less demanding than $I \leftrightarrow II$.

The tsunami case illustrates this point well. Given its default status as Conflicted C2, this collective organization clearly exhibited minimal C2 maturity. This makes sense, for the collective had only just formed, and it had done so through an ad-hoc collection of diverse organizations—many of which had never worked together before—each with its

own agenda, personnel and operating procedures. Although each individual organization had its own C2 approach, there was no C2 in place for the collective as a whole, and the various organization participants were conflicting with one another's goals and activities. Moreover, given the seeming infeasibility of transitioning to Deconflicted C2 noted previously, it appeared as though the collective was stuck in Conflicted C2.

Alternatively, if the collective organization were to recognize the potential to increase maturity and transition to Edge C2 directly, then many of its problems may have been mitigated or even obviated. If, for instance, participants were to realize that no one was in charge *of the collective*—hence ADR for the collective is maximal—and that every organization within such collective was free to interact with every other one—hence PoI for the collective is maximal—then they could see how the C2 approach for the collective would be located well to the right and up on the C2 design space (i.e., broad ADR and loose PoI, but narrow DoI).

The last step would be the most important: The collective would need to share information abundantly—hence maximize DoI for the collective—in order for its diverse participants to operate at the high maturity level associated with Edge C2. Notice that no individual organization needs to transition to Edge C2 for its own operations. Rather, the organization collective as a whole needs to transition to Edge C2.

For instance, say that one, single organization (e.g., the US Military) were to take on the role of information collector-disseminator. This could involve setting up, for instance, an ad-hoc cell or wireless network and encouraging all organization participants to utilize simple webpages or like sites to post, share and receive information regarding their goals, operations, needs and timeframes. Such sites might also outline how the Edge C2 approach works, and it could encourage individual participants to seek out information and assistance from one another.

If individual organizations (e.g., militaries, NGOs, Indonesian Government) were to find value in the information, then they might become motivated to contribute to the information collective, and with a realization that the organizations' diverse goals and activities were experiencing less conflict—and hence the collective organization was becoming more effective—a transition to Edge C2 could become feasible. Indeed, such

transition to Edge C2 would remain more feasible than one to Deconflicted for the collective.

As above, what began as theory comes now to practice. With a realistic, contemporary scenario suggesting a transition to higher maturity C2 for a disaster relief organization collective, not only do we have theory to guide such transition, we also have a set of concrete and discrete steps to effect it. Moreover, in addition to documenting the theory and corresponding practice through this technical report, the associated new knowledge represents something that can be taught in military schools, formulated through standard operating procedures (SOPs), along with techniques, tactics and procedures (TTPs), and practiced through training exercises. Another considerable step forward in terms of C2!

V. CONCLUSION

The technologic capabilities of autonomous systems (AS) continue to accelerate, 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 through our recent research—representing the current state of the art—we have demonstrated computational experimentation capability in the TASP domain.

We have also elucidated several technology trends indicating that unmanned aircraft may be diverging away from operating and behaving like their manned counterparts, even though phenomena such as swarming and mission integration appear to be upon us. This stream of research seeks to stay five to ten years ahead of practice, which enables us to anticipate both issues and opportunities in an area that remains under researched: C2 of autonomous systems.

In this technical report, we build upon our computational experiments to address how TASP C2 can be designed for asymmetric advantage, with particular emphasis on dynamic design. After summarizing important background information, which includes a description of the POWer computational environment, its three implications, and a JTF model example, we also incorporate findings from prior research on next generation autonomous systems and their corresponding models. An overview of the research method follows, with many details of computational modeling and experimentation moved to an appendix to maintain focus and concision.

Then we describe the key results, which begin with an overview and continue with articulation of a multidimensional approach space (i.e., a design space) for visualizing and analyzing different C2 designs. This design space centers on three interdependent dimensions: *allocation of decision rights*, *patterns of interaction* and *distribution of information*, which are depicted graphically as orthogonal and used to delineate alternate C2 design points (e.g., traditional military organization, Edge organization). This discussion continues further with conceptualization of five C2 design archetypes (i.e., Conflicted, Deconflicted, Coordinated, Collaborative, Edge), each of

which is unique theoretically and can be related to a C2 design point in practice. As a set they comprise a useful and distinct collection of reference points.

We show graphically and analytically how the five archetypes plot along a rough diagonal in the C2 design space, and we relate their relative ordinal position along such diagonal in terms of C2 maturity, which captures in part an organization's capability to operate effectively in ever more challenging mission-environment conditions. We discuss further how organizations at higher maturity levels develop the ability to operate across a larger volume of the C2 Space, which includes the ability to transition to lower maturity C2 designs. Of course, increased maturity comes at a cost. Not only must an organization expend considerable time and energy to transition from one maturity level to another, but speaking generally, the higher the C2 design, the greater the coordination effort required.

This introduces the concept of dynamic C2 design. Because no single C2 design is most appropriate for all missions and environments at all times, we describe the need for transition from one C2 design or approach to another, which elucidates well the underlying need for dynamic C2 design. The central idea of dynamic C2 design is for an organization to shift from one C2 approach to another—perhaps even temporarily, in response to a mission change or natural disaster, for two instances—as diverse missions and environments necessitate. However, in something of a Markov sense, an organization's current C2 design appears to constrain which alternate designs are possible in terms of transition.

Hence we divide the five archetypical C2 designs into two categories: conventional and unconventional. Three, comparatively common and familiar C2 design archetypes are included in the conventional category (i.e., Deconflicted, Coordinated, Collaborative), the transitions between which are relatively straightforward and linear. Two, relatively less common and familiar archetypes are included in the unconventional category (i.e., Conflicted, Edge), the transitions between which are comparatively complex.

Dividing our discussion between the conventional and unconventional C2 designs, we outline a number of transition rules and guides for each. For conventional C2 designs, as an example, we outline dynamic C2 design in terms of three steps, which we illustrate via a US Military organization required to transition between C2 designs in

order to accommodate changes in manned and unmanned aircraft operations at sea. This provides guidance for a Commander interested in formulating and communicating actionable intent, and it helps the Commander's staff and subordinate leaders in satisfying such intent.

For unconventional C2 designs, as an example, we link the extreme C2 design archetypes (i.e., Conflicted, Edge) and delineate how the distance (e.g., consider the degree of organization change required and disruption experienced) associated with a transition between these two can be less than between designs points that are closer together in terms of maturity (e.g., Conflicted, Deconflicted). This is illustrated via a disaster relief effort undertaken by myriad, diverse, unaffiliated organizations and viewed through the lens of an ad-hoc collective. The illustration elucidates a severe lack of efficacy that can afflict the organization collective due to Conflicted C2—even though each individual organization may operate well through its own C2 approach—in addition to a set of steps that can be taken to facilitate a transition out of its pathologic, Conflicted C2 design.

The ability to transition dynamically between alternate C2 designs provides a novel capability to align an organization's C2 approach with the peculiarities of its mission-environment context, peculiarities which can be ephemeral and difficult to anticipate. Such capability enhances organization agility, which can enable asymmetric advantage; that is, an agile organization, which is able to transition dynamically between alternate C2 designs, can outperform otherwise peer or equivalent organizations lacking such ability. Further, not only do we describe what such dynamic C2 design would entail, we also articulate how to effect it in practice. This represents a substantial finding and research contribution.

Future research can extend this work through three complementary lines: Case study, computational experimentation, and Fleet implementation. Through the first, researchers can embed themselves within an operational organization and examine in detail how C2 associated with both manned and unmanned aircraft systems is conducted. This would be to document and understand in detail the current C2 design point (C2c). Analysis and interaction with participants could then help to instantiate one or more

desired design points (C2d) and to lay out organizationally feasible transitions to increasingly mature C2 approaches.

Through the second, researchers can use results from such case study to further enhance our computational models, which in turn can be run through the next set of experiments to assess different modes, techniques and timings of dynamic C2 design transitions. Different C2 designs may become relatively more or less appropriate depending upon a variety of different mission-environment contexts—a dependence which remains unknown at present—and situated Commander's intent will need to account for such dependence directly. Better to assess the C2 design space computationally and systematically, across a variety of mission-environment contexts, than to leave our organizations learning by trial and error at sea.

Through the third, as noted above, what began as theory comes now to practice. Dynamic C2 design—especially as it centers on understanding both current and desired C2 design archetypes, along with organizationally feasible transitions—represents something that can be taught in military schools, formulated through standard operating procedures (SOPs), along with techniques, tactics and procedures (TTPs), and practiced through training exercises. Researchers can become instrumental in helping to prepare the learning materials to be taught in military schools, through drafting SOPs, TTPs and like procedures, and through assistance with training exercises. This epitomizes the transfer of knowledge from the research laboratory to practical application at sea.

VI. REFERENCES

- Adams, C. March 2014. *FACE Software Effort Builds Momentum* Avionics magazine available at: aviationtoday.com/av/military/FACE-Software-Effort-Builds-Momentum_81308.html#.VggogM_luos.
- Alberts, D.S. & Hayes, R.E. 2003. *Understanding: Command and Control* Washington, DC: Command and Control Research Program.
- Alberts, D.S. & Nissen, M.E. 2009. Toward Harmonizing Command and Control with Organization and Management Theory. *International C2 Journal* 3(2): 1-59.
- AMoD. 2001. Aviation history as Global Hawk completes US-Australia flight. Australian Ministry of Defence press release (24 April 2001); accessed from Wikipedia website: http://en.wikipedia.org/wiki/Northrop_Grumman_RQ-4_Global_Hawk ; retrieved on 27 January 2014.
- Bamberger, R.J., Jr., Watson, D.P., Scheidt, D.H. & Moor, K.L. 2006. Flight Demonstrations of unmanned Aerial Vehicle Swarming Concepts, John Hopkins APL Technical Digest, 27(1): 41-55.
- BBC. 11 July 2013. US drone lands on aircraft carrier. acc from Wikipedia website: http://en.wikipedia.org/wiki/Northrop_Grumman_X-47B#cite_note-BBC11July2013-4 ; retrieved 27 January 2014.
- Bourne, D. May 2013. My Boss the Robot. *Scientific American* 38-41.
- Brown, E. August 2015. *UAVs Learn to Fly Solo*. MIT News available at www.news.mit.edu.
- Christiansen, T.R. 1993. Modeling Efficiency and Effectiveness of Coordination in Engineering Design Teams. Unpublished Ph.D Dissertation. Stanford University.
- CFFC. 2014. *Fleet MQ-8B/C Fire Scout and MQ-4C Triton Unmanned Aircraft System (UAS) Platform Wholeness Concept of Operation*. US Fleet Forces Command.
- Clear Path Robotics. 2009 TurtleBot 2 Open-source robot development kit for apps on wheels. Available at: <http://www.turtlebot.com/>
- Codella, C. December 2012. *The Era of Cognitive Systems: An Inside Look at IBM Watson and How it Works*. REDP-4955-00.
- Cohen, G.P. 1992. The Virtual Design Team: An Information Processing Model of Design Team Management. Unpublished Ph.D Dissertation. Stanford University.

Condon, B., Fahey, J., Rugaber, C., Lee, Y., Sterling, T. & Kurtenbach, E. January 24, 2013. *Practically human: Can smart machines do your job?* Associated Press.

Couts, A. September 12, 2012. Drones: 13 things you need to know from Congress's new report. *Digital Trends*; <http://www.digitaltrends.com/cool-tech/drones-congressional-research-service-report/#ixzz2fLx8ZLq4> ; retrieved 09/28/2012.

Defense Science Board – Task Force Report. 2012. The Role of Autonomy in DoD Systems. Available at <http://fas.org/irp/agency/dod/dsb/autonomy.pdf>.

DoDD 3000.09. November 21, 2012. Department of Defense Directive 3000.09, Autonomy in Weapon Systems.

DoD Data Rights Team. June 2013. DoD Open Systems Architecture Contract Guidebook for Program Managers v.1.1 available at https://acc.dau.mil/adl/en-US/631578/file/73333/OSAGuidebook%20v%201_1%20final.pdf.

Dolgin, D., Wasel, B. & Langelier, M. June 1999. Identification of the Cognitive, Psychomotor, and Psychosocial Skill Demands of Uninhabited Combat Aerial Vehicle (UCAV) Operators. Naval Air Systems Command technical report; DTIC code19991004 162; retrieved 11/05/2012.

Doshi, F. & Roy, N. March 2007. Efficient Model Learning for Dialogue Management. Proceedings of the 2007 2nd ACM/IEEE International Conference on Human-Robot Interaction. Arlington, VA.

Feil-Seifer, D. & Mataric, M.J. 2005. Defining Socially Assistive Robotics. Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, Chicago, IL.

Galbraith, J.R. 1977. *Organizational Design*. Addison-Wesley.

Gateau, J.B., Leweling, T.A., Looney, J.P. and Nissen, M.E. June 2007. Hypothesis Testing of Edge Organizations: Modeling the C2 Organization Design Space. Proceedings International Command & Control Research & Technology Symposium, Newport, RI; Winner – Best Student Paper Award.

Ghanadan, R. February 2011. Mathematics of Sensing, Exploitation and Execution (MSEE), Available at <http://www.darpa.mil/program/mathematics-of-sensing-exploitation-and-execution>.

Glaser, B.G. & Strauss, A.L. 1967. *The Discovery of Grounded Theory: Strategies for Qualitative Research*, Chicago, Aldine Publishing Company.

Hambring, D. April 2015. *A drone that learns*. New Scientist Magazine issue 3017 Available at <https://www.newscientist.com/> and MIT News www.mit.edu/newsoffice/

- Hogg, 2009. *The Unmanned Imperative*, CNO Strategic Studies Group XXVIII.
- HRW. November 19, 2012. Human Rights Watch. Losing Humanity: The Case Against Killer Robots.; <http://www.hrw.org>; retrieved 11/26/2012.
- Jin, Y. & Levitt, R.E. 1996. The Virtual Design Team: A Computational Model of Project Organizations. *Journal of Computational and Mathematical Organizational Theory* 2(3): 171-195.
- Johnson, E.N, Proctor, A.A, Ha, J. and Tannenbaum, A.R.. December 2004. *Development and Test of Highly Autonomous Unmanned Aerial Vehicles*, Journal of Aerospace Computing, Information, and Communication Vol. 1.
- Joyce, J.J. 5/10/2012. Scan Eagle UAS Deploying Aboard Coast Guard National Security Cutter, Navy.mil The Source for Navy News, Story Number: NNS120510-26; http://www.navy.mil/search/print.asp?story_id=67101; retrieved 01/19/2013.
- Keller, J. March 2010, *Air Force to use artificial intelligence and other advanced data processing to hit the enemy where it hurts*. Military & Aerospace Electronics magazine.
- Keller, J. January 2015, *Artificial intelligence and new levels of machine learning are aims of IARPA MICrONS program*. Military & Aerospace Electronics magazine.
- Kunz, J.C., Levitt, R.E. & Jin Y. 1999. The Virtual Design Team: A computational model of project organizations. *Communications of the Association for Comp. Machinery* 41(11): 84-92.
- Law, A.M. & Kelton, D. 1991. *Simulation Modeling and Analysis* 2nd Ed., New York, NY, McGraw-Hill.
- Levitt, R.E. 2004. Computational Modeling of Organizations Comes of Age. *Journal of Computational and Mathematical Organization Theory* 10(2): 127-145.
- Levitt, R.E., Orr, R.J. & Nissen, M.E. 2005. Validating the Virtual Design Team (VDT) Computational Modeling Environment. The Collaboratory for Research on Global Projects, Working Paper #25, 1-15. Available at: http://crgp.stanford.edu/publications/working_papers/WP25.pdf
- Levitt, R.E., Thomsen, J., Christiansen, T.R., Kunz, J.C, Jin, Y. & Nass, C. 1999. Simulating Project Work Processes and Organizations: Toward a Micro-Contingency Theory of Organizational Design. *Management Science* 45(11): 1479-1495.
- March, J.G. & Simon, H.A. 1958. *Organizations*. New York: Wiley.

McFarlane, D., Sarma, S., Chirn, J.L., Wong, C.Y. & Ashton, K. June 2003. Auto ID systems and intelligent manufacturing control, *Engineering Applications of Artificial Intelligence* 16(4): 365–376.

Muller, J. 9/26/2012. With Driverless Cars, Once Again It Is California Leading The Way. *Forbes*; <http://www.forbes.com/sites/joannmuller/2012/09/26/with-driverless-cars-once-again-it-is-california-leading-the-way/>; retrieved 09/19/2013.

NAVAIR News. November 2011. *Navy completes UAS Common Control System demo*. Available at: <http://www.navair.navy.mil/index.cfm?fuseaction=home.NAVAIRNewsStory&id=4818>

Nissen, M.E. 2013. *Introduction to Command and Control* Naval Postgraduate School CC3000 course, Monterey, CA.

Nissen, M.E. & Buettner, R. June 2004. Computational Experimentation: Bridging the Chasm between Laboratory and Field Research in C2. *Proceedings* Command and Control Research and Technology Symposium, San Diego, CA.

Nissen, M.E. & Place, W.D. June 2013. Archetypical C2 Organization Design for Ever Increasing Technologic Autonomy: An Unmanned Aircraft System Illustration. *Proceedings* International Command & Control Research & Technology Symposium, Alexandria, VA.

Nissen, M.E. & Place, W.D. December 2014, Computational Experimentation to Understand C2 for Teams of Autonomous Systems and People. *Proceedings* International Command & Control Research & Technology Symposium, Alexandria, VA.

Nissen, M.E. & Place, W.D. November 2016. Command and Control for Teams of Autonomous Systems and People. Technical Report NPS-16-001, Naval Postgraduate School, Monterey, CA.

Oh, R.P.T, Sanchez, S., Lucas, T., Wan, H. & Nissen, M.E. 2010. Efficient Experimental Design Tools for Exploring Large Simulation Models. *Computational and Mathematical Organization Theory* 15(3): 237-257; DoI 10.1007/s10588-009-9059-1.

Place, W.D. & Nissen, M.E. 2015. Command and Control Models of Next Generation Unmanned Aircraft Systems. Technical Report NPS-IS-15-002, Naval Postgraduate School, Monterey, CA.

Roff, H. August 2015, *The International-Relations Argument Against Killer Robots*. Available at: <http://www.defenseone.com/ideas/2015/08/international-relations-argument-against-killer-robots/119275/>.

SAS065. 2008. The Indian Ocean Tsunami: The case of Aceh and North Sumatra. NATO RTO SAS-065 Report.

Selby, G. 2015, Robots Learn to Perform Tasks by “Watchin” Videos. Available at <http://science.dodlive.mil/2015/08/22/robots-learn-to-perform-tasks-by-watching-videos/>.

Simon, H.A. 1991. *Bounded Rationality and Organizational Learning*. Cambridge, MA: MIT Press.

Strauss, A.L. & Corbin, J. 1998. *Basics of Qualitative Research – Techniques and Procedures for Developing Grounded Theory* (2nd Edition) Sage Publications: London.

Thompson, J.D. 1967. *Organizations in Action*. New York, McGraw-Hill.

Thomsen, J. 1998. The Virtual Team Alliance (VTA): Modeling the Effects of Goal Incongruency in Semi-Routine, Fast-Paced Project Organizations. Stanford Univ.

Warne, D. 2015. *Pulse-coupled Neurral Network Performance for Real-time Identification of Vegetation During Forced Landing*. ANZIAM Journal, 5

Work, R. June 2015. Deputy Secretary of Defense Speech at the China Aerospace Studies Institute. As Delivered by Deputy Secretary of Defense Bob Work, RAND Corporation, Arlington, VA. Available at: <http://www.defense.gov/News/Speeches/Speech-View/Article/606683>

THIS PAGE INTENTIONALLY LEFT BLANK

VII. 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 empiric 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 2. 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* represent 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 2 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 3.

Table 3 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 days²), 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 Medium³ 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-

² 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.

³ Most ordinal parameters are set nominally at Medium throughout POWer. This establishes and maintains a stable baseline for comparison across various models and runs.

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 4.

Table 4 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 levels⁴ 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

⁴ 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.

L4 & L5 advanced UAVs). These positions correspond to the command/staff and operations tasks summarized above; that is, the CTF position (e.g., commander and staff) performs the CTF tasks, the CTG⁵ 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.

⁵ 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 5.

Table 5 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 model⁶. Each of these model parameters ranges from Low to High.

Communication Prob refers to the likelihood that any particular task in the model will require communication with another one; this parameter centers on (green)

⁶ 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 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 6. Parameter settings under the “Pooled” column correspond with those listed above and elsewhere as “baseline” values in the model.

Table 6 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 7.

Table 7 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 *integrationaly* (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.

VIII. APPENDIX B

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

A. NUMERIC RESULTS

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

1. Duration

Table 8 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 8 Simulation Results – Duration

Level	Ship	Duration		(hrs x 10)	
		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 close⁷ 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

⁷ 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 condition⁸. 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 9 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.

⁸ 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 9 Simulation Results – Rework

Level	Ship	Rework Aircraft	Pool	(p-hrs x 10)	
				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 10 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 10 Simulation Results – Coordination

Level	Ship	Coordination		(p-hrs x 10)	
		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 11 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 11 Simulation Results – Wait

Level	Ship	Wait Aircraft	Pool	(p-hrs x 10)	
				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 12 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 12 Simulation Results – Work Cost

Level	Ship	Work Cost		(\$k x 10)	
		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 13 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 13 Simulation Results – Functional Risk

Level	Ship	Functional Risk		(% / 100)	
		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 14 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 14 Simulation Results – Mission Risk

Level	Ship	Mission Risk		(% / 100)	
		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 15 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 15 Simulation Results – Maximum Backlog

Level	Ship	Backlog Max		(hrs x 10)	Integ
		Aircraft	Pool	Recip	
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. GRAPHIC RESULTS

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

1. Duration

Figure 7 summarizes duration results graphically. This is the same figure presented in the body of this report above and is included here among details for reference. These graphical values match the numerical results presented 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 the table. 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 the table. 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 the table.

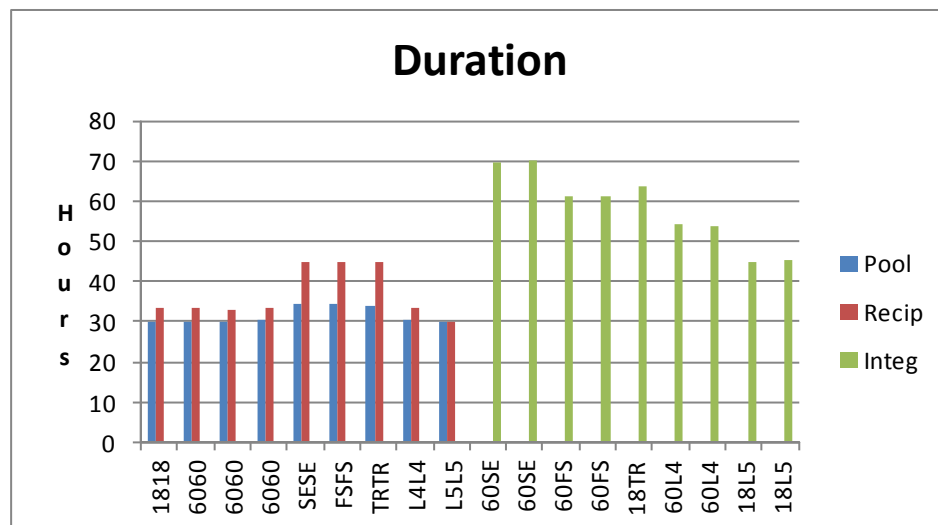


Figure 7 Graphical Summary – Duration

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 the table. 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 the table. 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 the table. 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 DDLG 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 the table.

Figure 8 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 the table. 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.

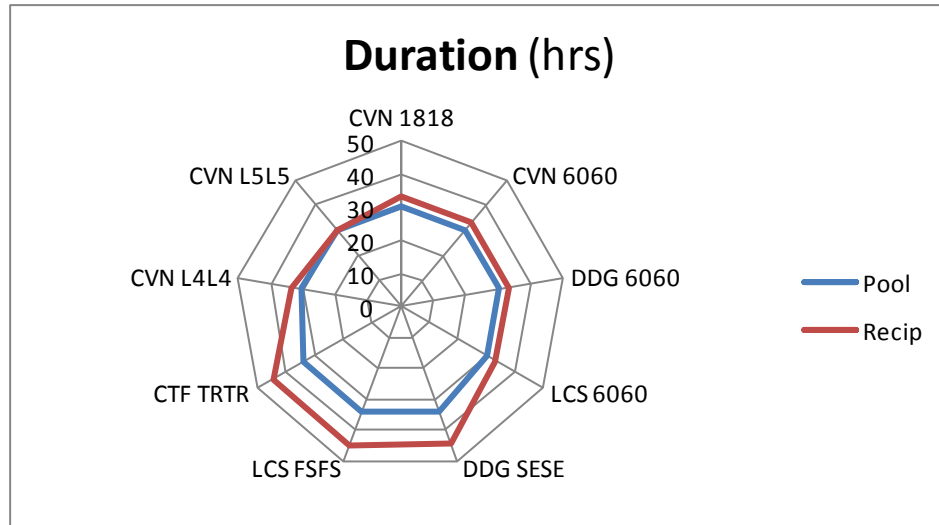


Figure 8 Combined Radar View – Duration

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 the table. 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 9 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.

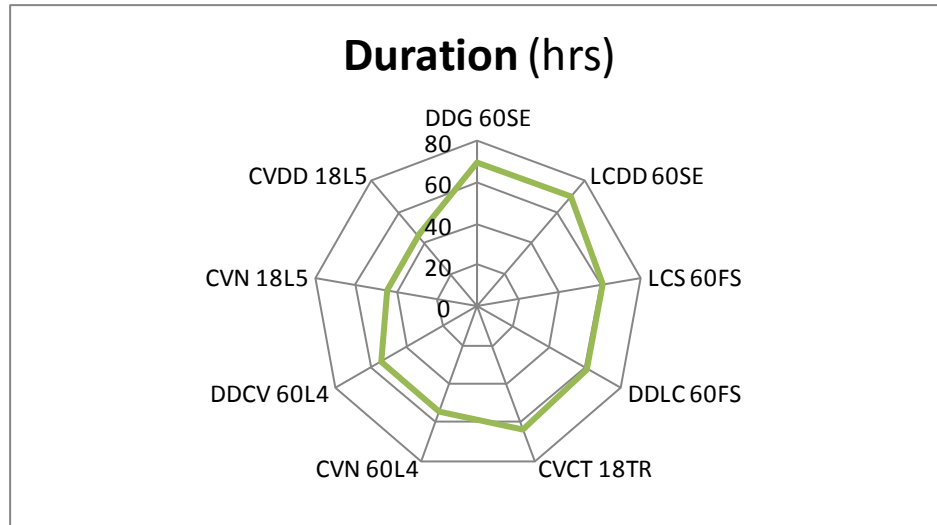


Figure 9 Mixed Radar View – Duration

2. Rework

Figure 10 summarizes rework results graphically. These graphical values (person-hours) match those presented in the table above and follow the same layout as described previously.

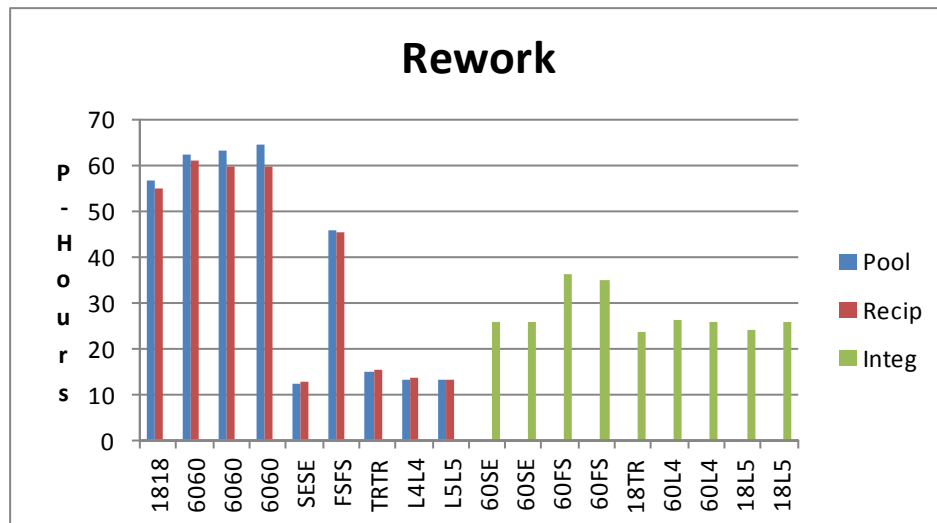


Figure 10 Graphical Summary – Rework

Figure 11 and Figure 12 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.

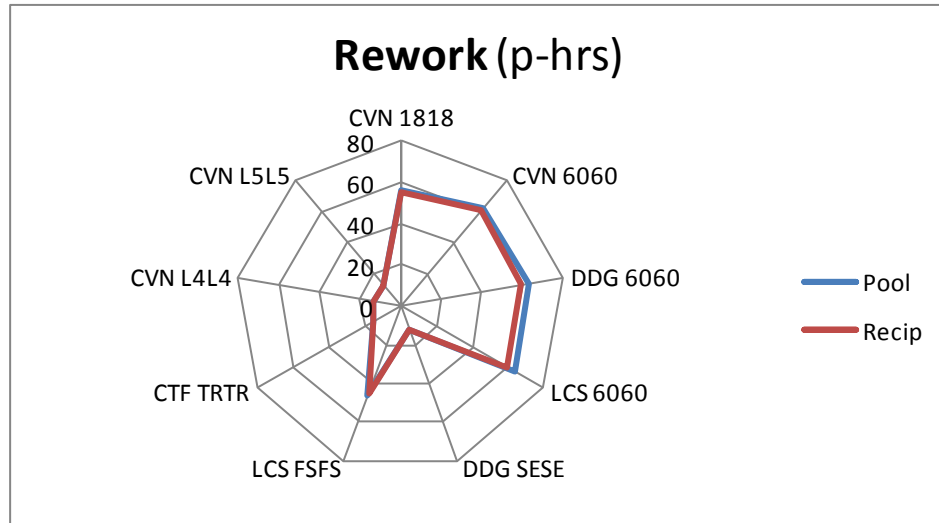


Figure 11 Combined Radar View – Rework

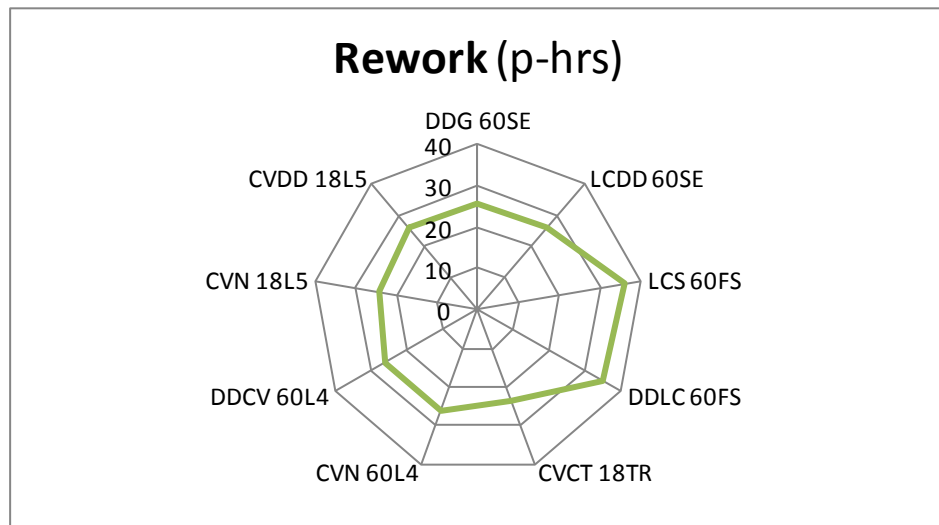


Figure 12 Mixed Radar View – Rework

3. Coordination

Figure 13 summarizes coordination results graphically. These graphical values (person-hours) match those presented in the table above and follow the same layout as described previously.

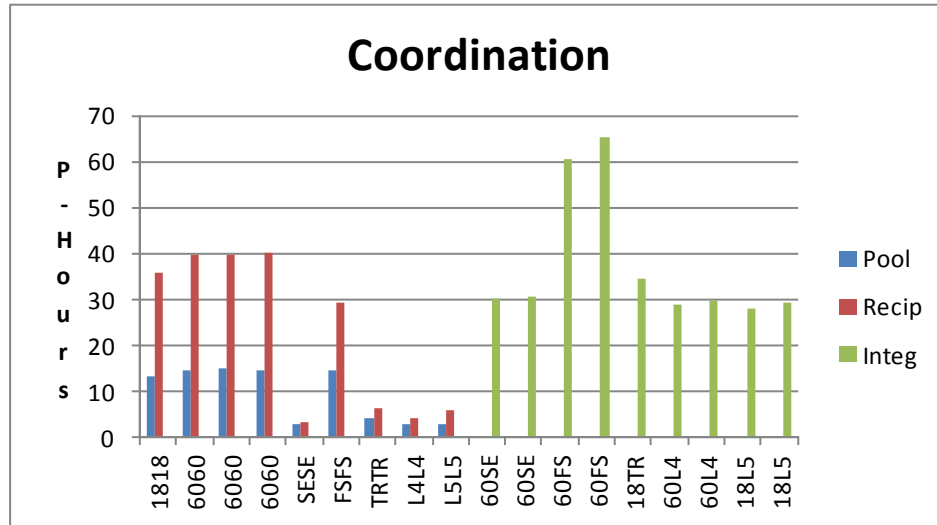


Figure 13 Graphical Summary – Coordination

Figure 14 and Figure 15 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.

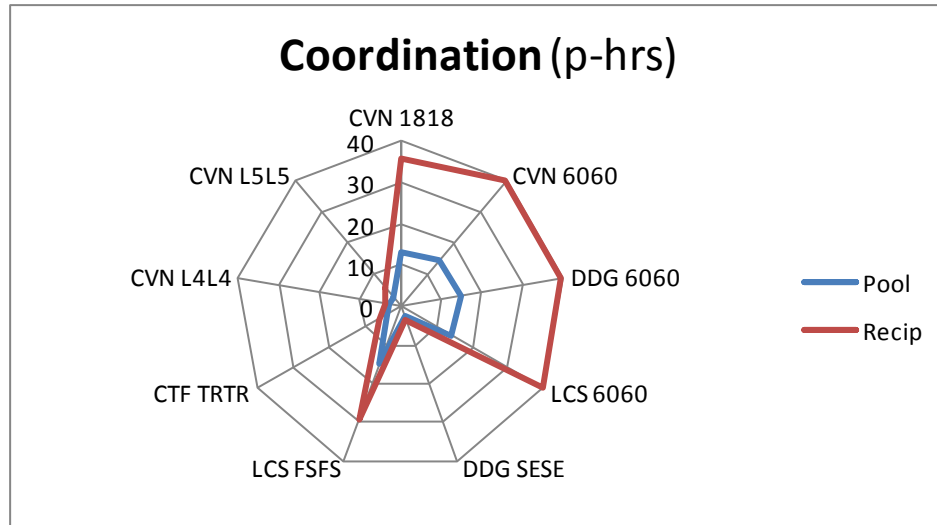


Figure 14 Combined Radar View – Coordination

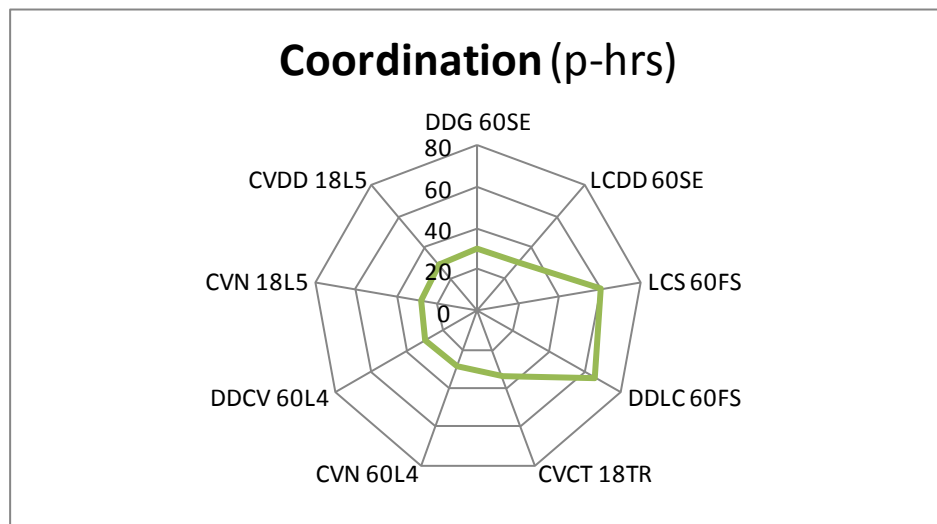


Figure 15 Mixed Radar View – Coordination

4. Wait

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

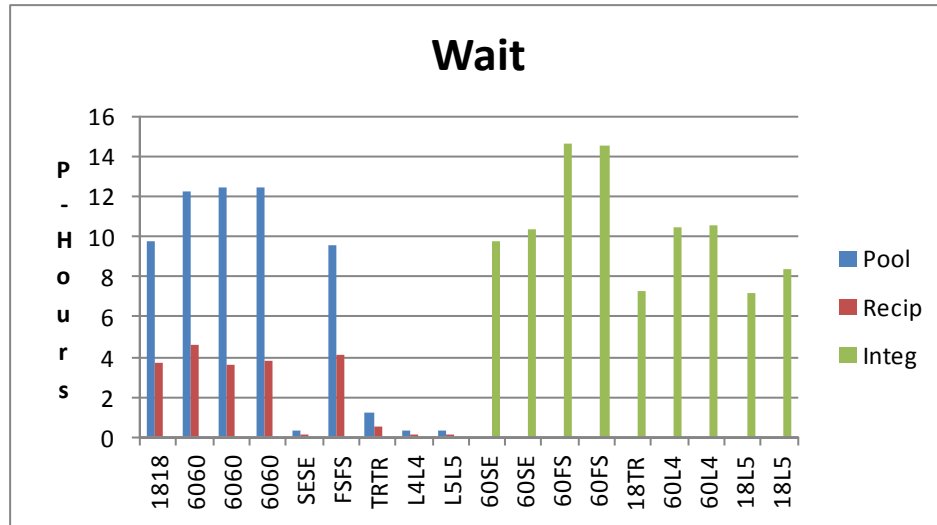


Figure 16 Graphical Summary – Wait

Figure 17 and Figure 18 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.

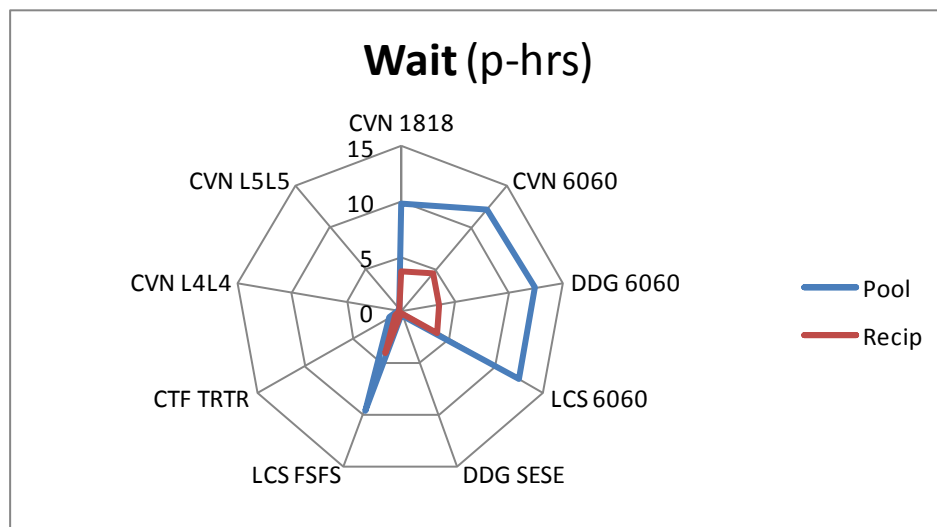


Figure 17 Combined Radar View – Wait

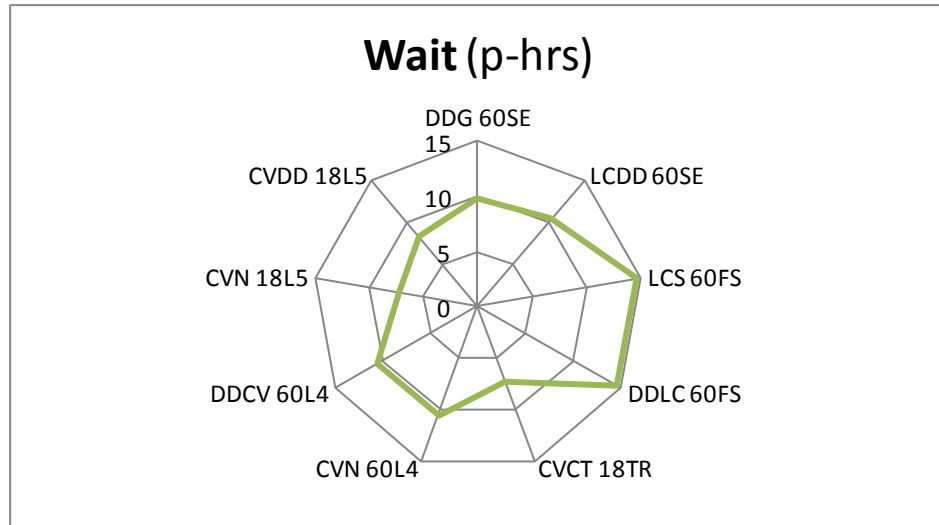


Figure 18 Mixed Radar View – Wait

5. Work Cost

Figure 19 summarizes work cost results graphically. These graphical values (\$k) match those presented in the table above and follow the same layout as described previously.

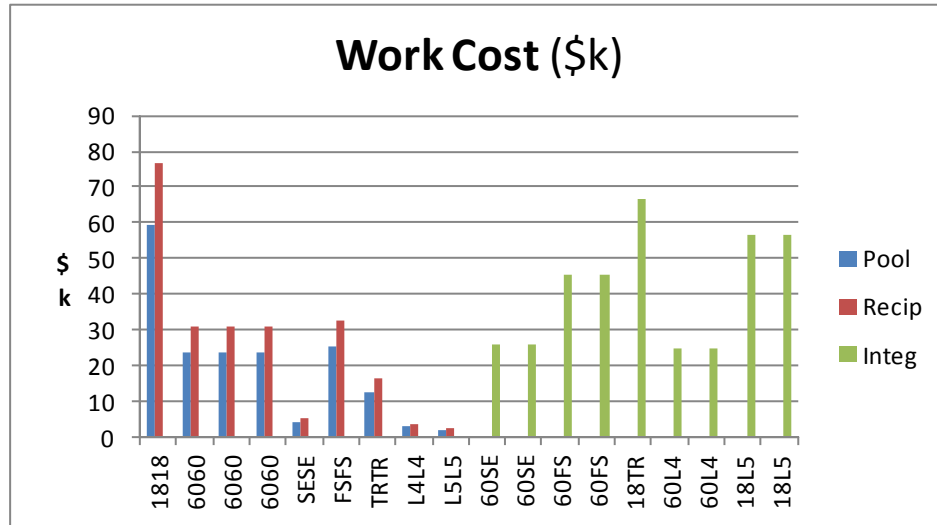


Figure 19 Graphical Summary – Work Cost

Figure 20 and Figure 21 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.

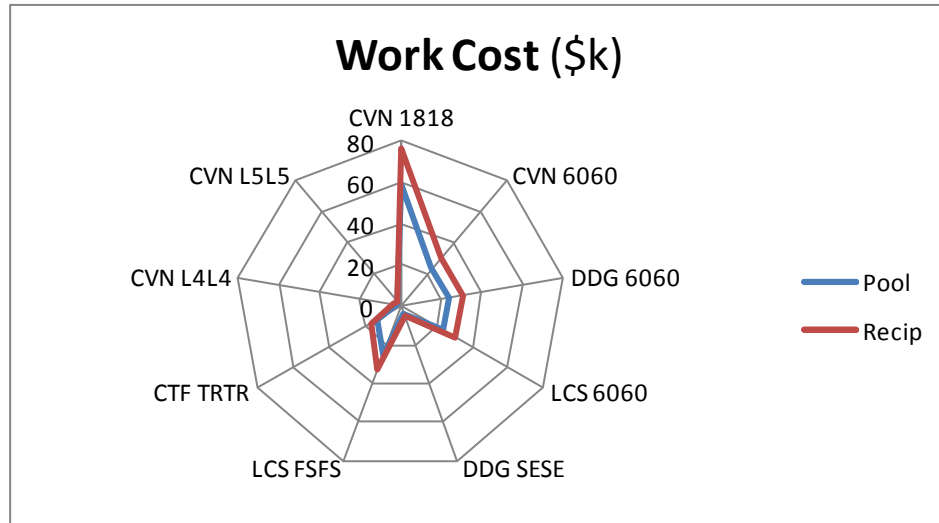


Figure 20 Combined Radar View – Work Cost

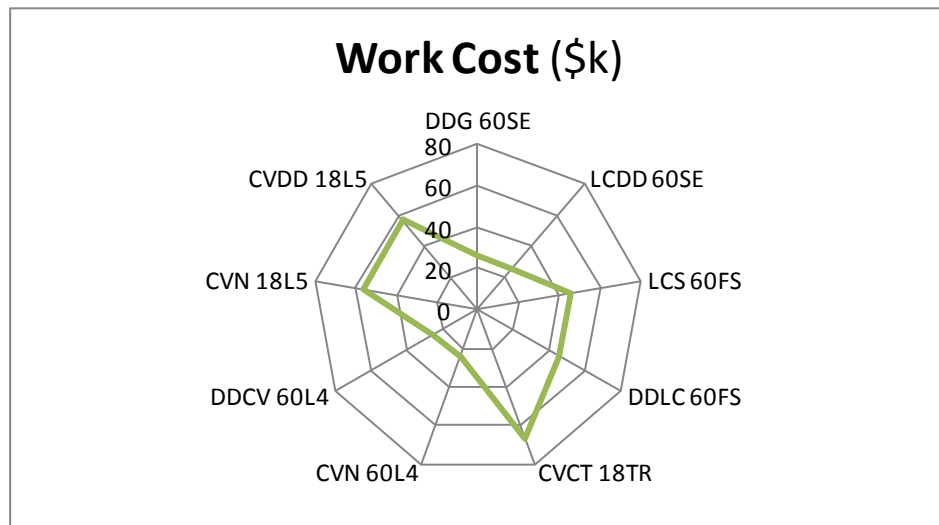


Figure 21 Mixed Radar View – Work Cost

6. Functional Risk

Figure 22 summarizes functional risk results graphically. These graphical values (%) match those presented in the table above and follow the same layout as described previously.

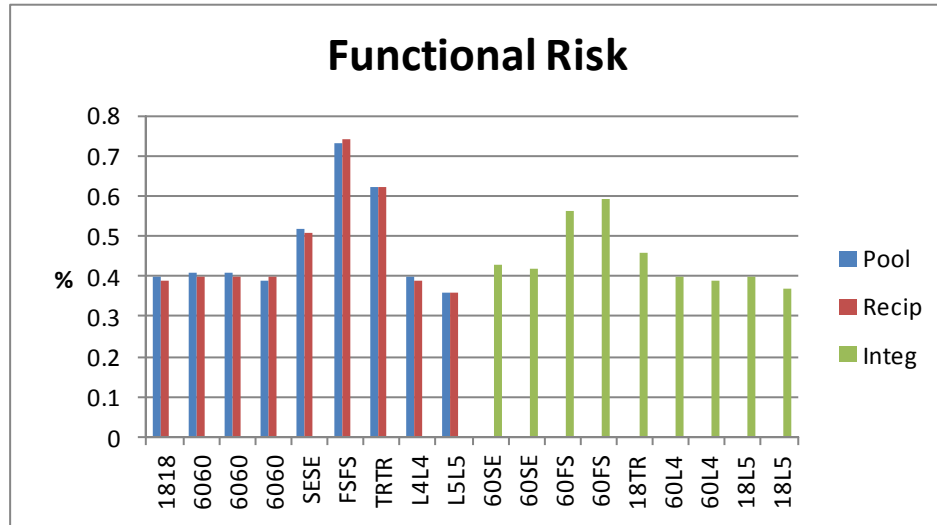


Figure 22 Graphical Summary – Functional Risk

Figure 23 and Figure 24 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.

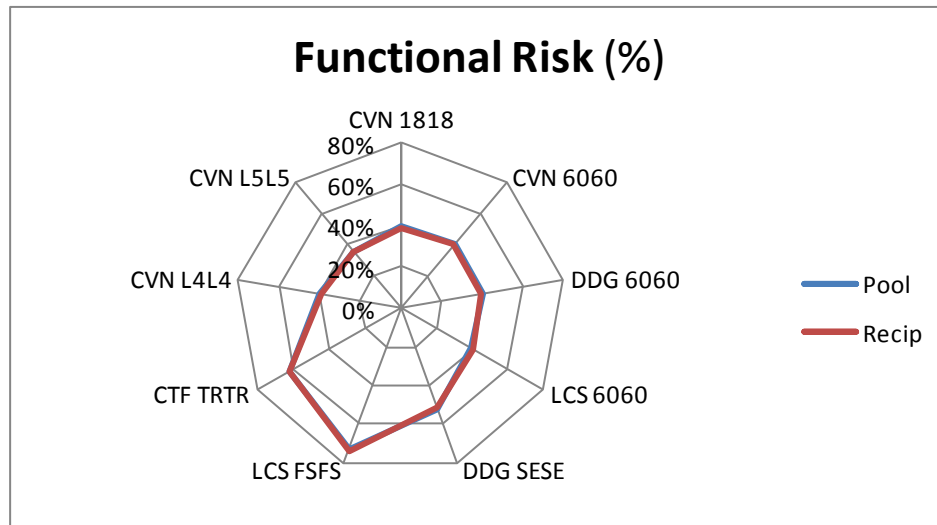


Figure 23 Combined Radar View – Functional Risk

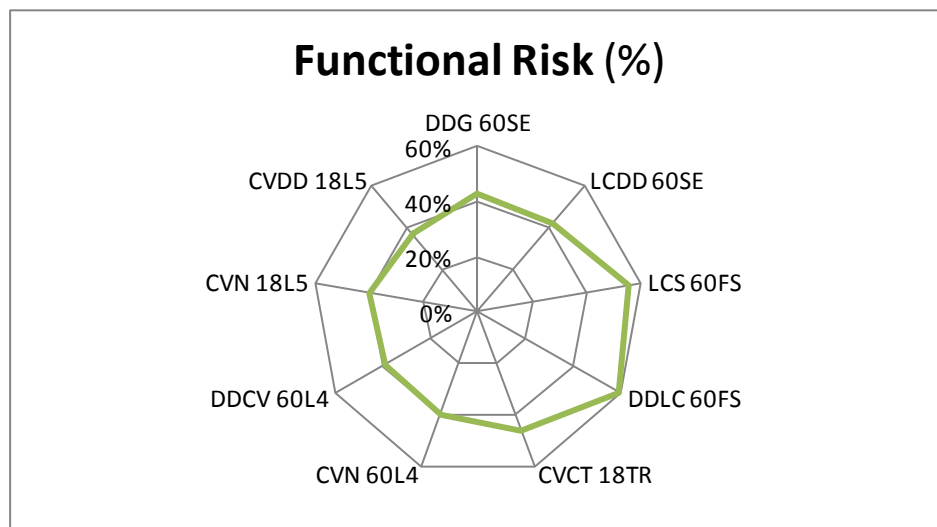


Figure 24 Mixed Radar View – Functional Risk

7. Mission Risk

Figure 25 summarizes mission risk results graphically. These graphical values (%) match those presented in the table above and follow the same layout as described previously.



Figure 25 Graphical Summary – Mission Risk

Figure 26 and Figure 27 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.

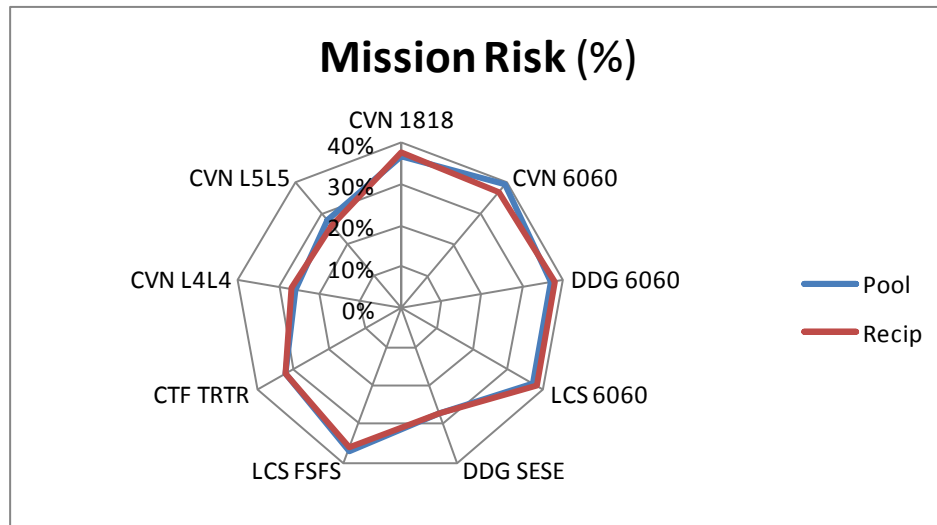


Figure 26 Combined Radar View – Mission Risk

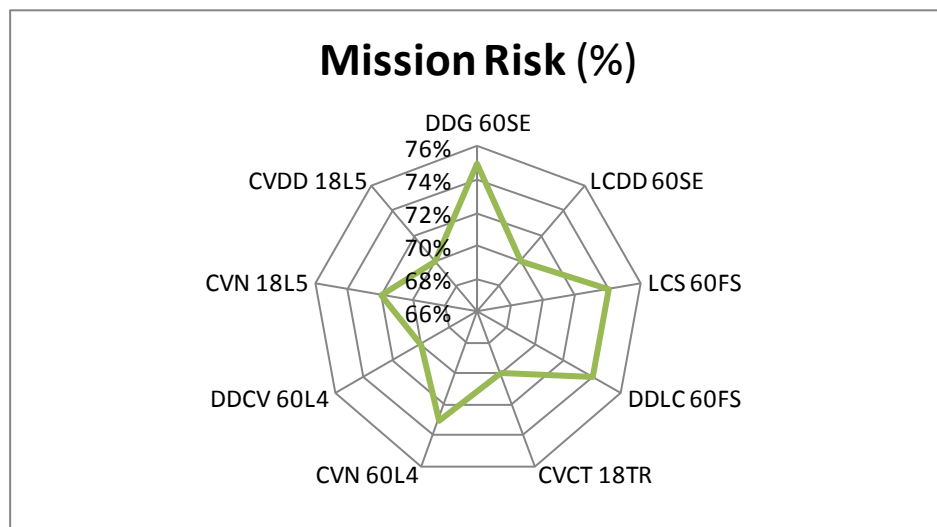


Figure 27 Mixed Radar View – Mission Risk

8. Maximum Backlog

Figure 28 summarizes maximum backlog results graphically. These graphical values (hours) match those presented in the table above and follow the same layout as described previously.

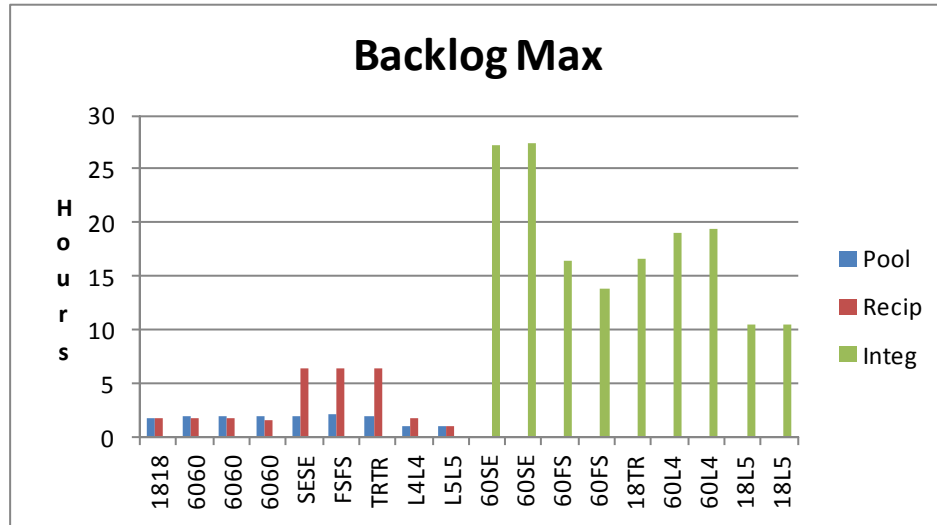


Figure 28 Graphical Summary – Maximum Backlog

Figure 29 and Figure 30 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.

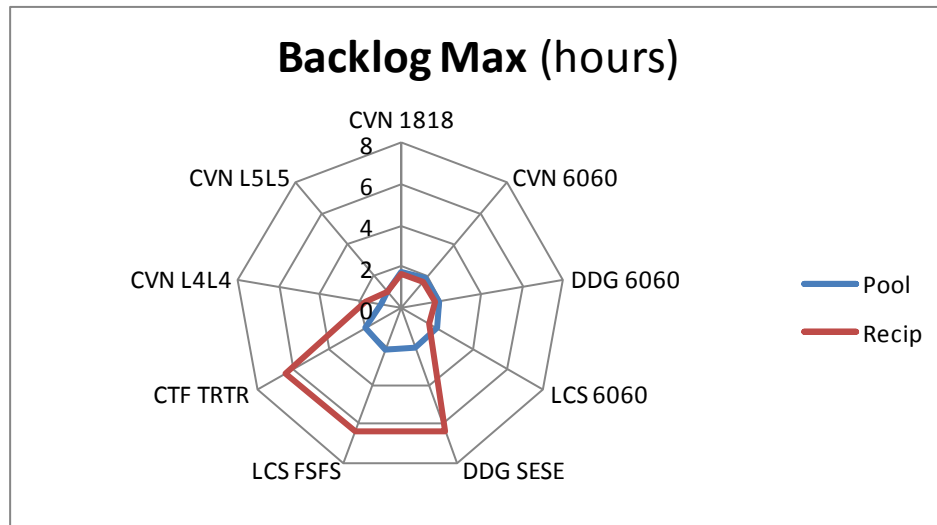


Figure 29 Combined Radar View – Maximum Backlog

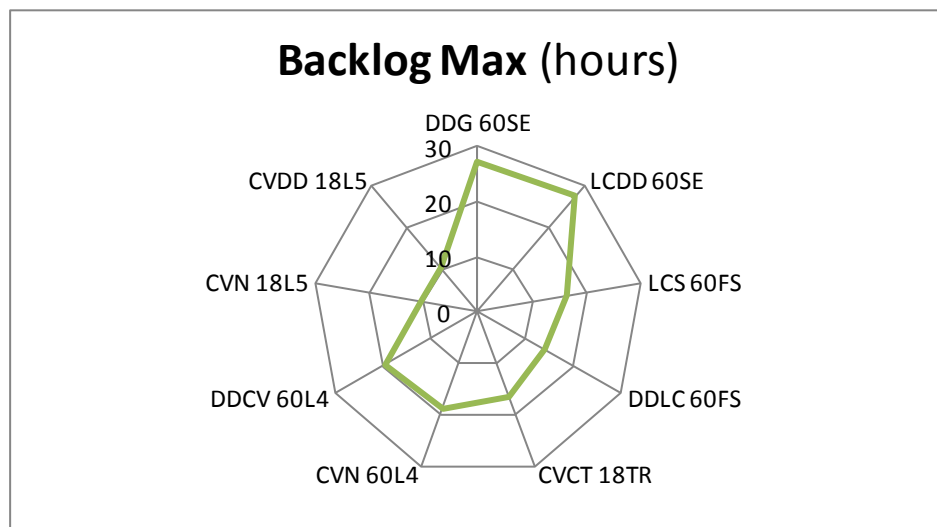


Figure 30 Mixed Radar View – Maximum Backlog

IX. APPENDIX C

In this appendix we include the detailed research method from our most recent project (Nissen & Place, 2016) to provide a convenient reference. This begins with a summary of the method, followed by description of the computational experiment design. We then outline the POWER specification and tailoring, and then summarize the controls, manipulations and measures employed in the experiments. In turn we describe the pooled, sequential, reciprocal and integrated computational models in considerable detail.

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.

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 empiric results for analysis.

Drawing heavily from Nissen and Place (2014), in the balance of this section we first summarize our computational experiment, then we outline the corresponding specification and tailoring of the 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 the 24 experiment conditions examined, organizing the discussion by interdependence level: pooled, sequential, reciprocal and integrated. This provides appropriate context for our work to analyze next generation AS capabilities for incorporation into the computational models and experiments.

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 16.

Table 16 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 ScanEagle⁹ 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 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 2) summarizes performance characteristics (e.g., *endurance*, *crew*, *cost per flight hour*, *required sorties*, *cost per head*) for each of the seven types of aircraft

⁹ Remote manual control is an option, but not required.

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 17 summarizes this interdependence scheme for the UAV domain.

Table 17 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 18. 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 18 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.

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 historically to emulate human behaviors, and the more sophisticated the AS, the more closely its behavior has mirrored 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 3) 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* duration¹⁰ set at 24 hours, and this planned duration is constant across all experiment cells.

Appendix A – Section C (see Table 4) 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—

¹⁰ 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.

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 5) 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.

2. Manipulations

Alternatively, Appendix A – Section E (see Table 6) 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 7) 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 31 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.

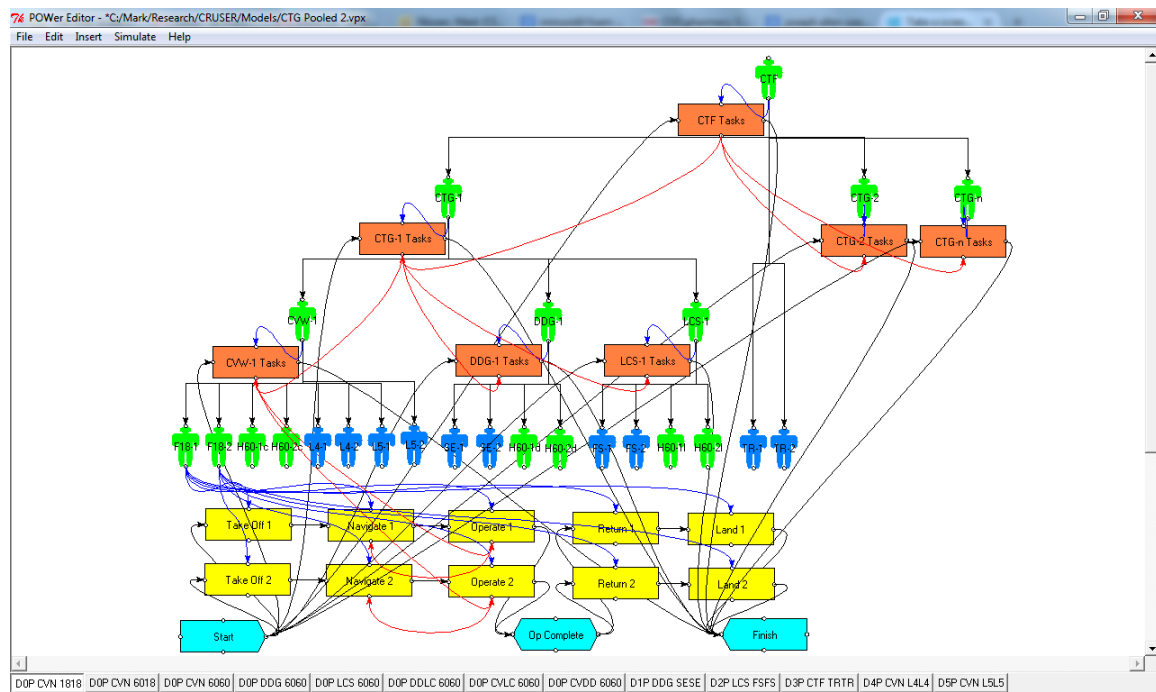


Figure 31 Baseline Model (D0P) – CVN F/A-18s

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 here¹¹. 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 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* duration¹² 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,

¹¹ 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).

¹² 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.

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 32. 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.

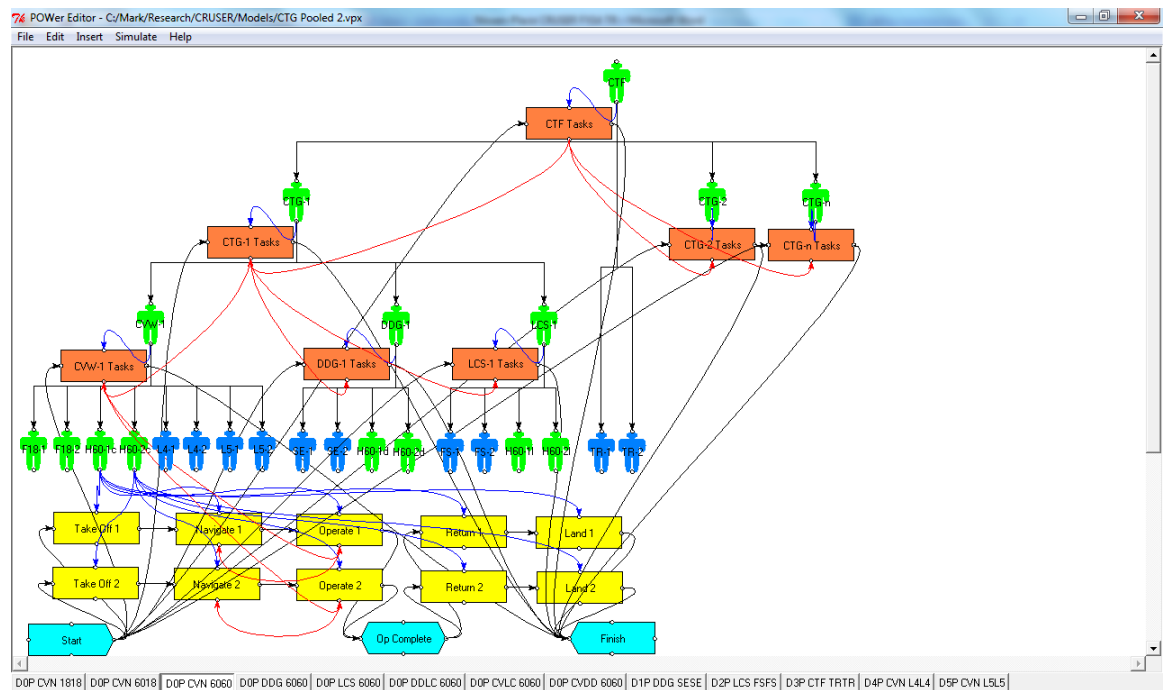


Figure 32 Baseline Model (D0P) – CVN MH-60s

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 33. 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).

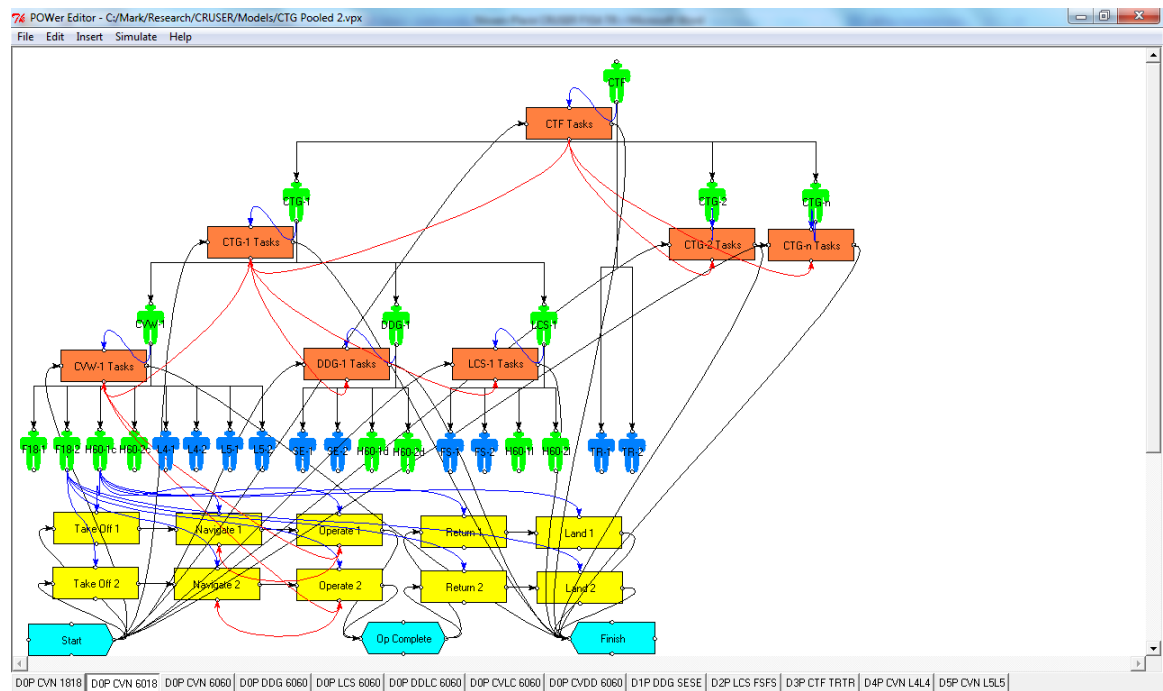


Figure 33 Baseline Model (D0P) – CVN F/A-18 & MH-60

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 34 delineates two helos operating from one or more DDG platforms¹³.

¹³ Another model (not shown) represents two MH-60s operating from one or more LCS ship platforms. C2 demands and implications are highly similar.

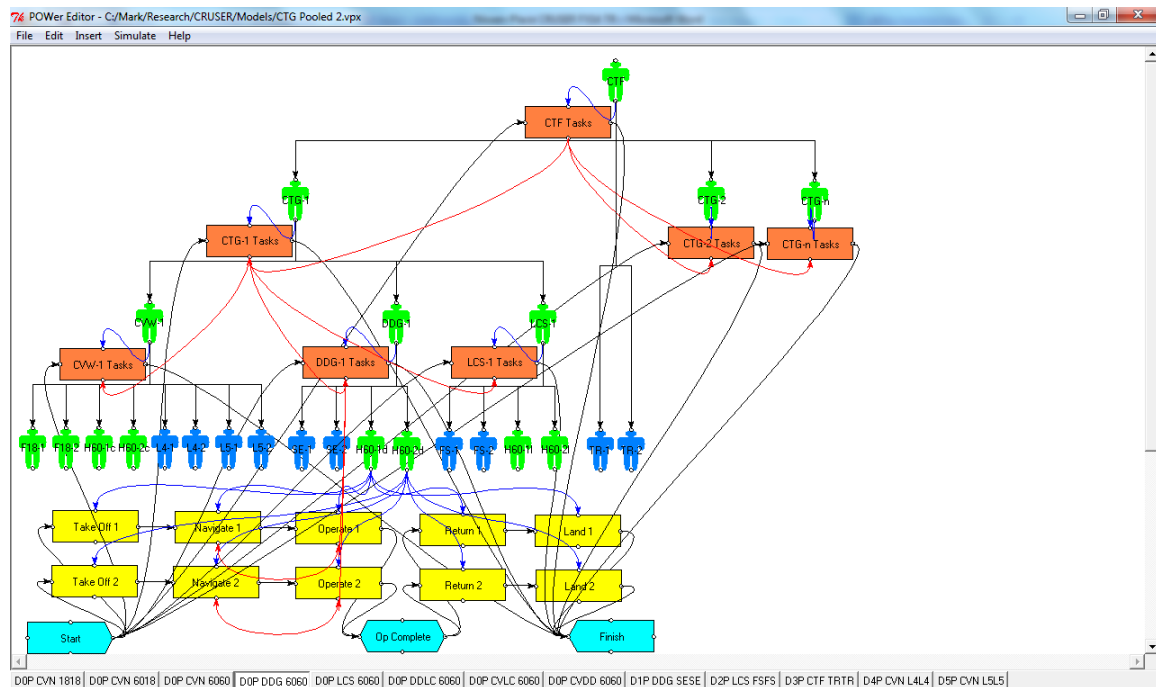


Figure 34 Baseline Model (D0P) – DDG MH-60s

Still further, suitably capable aircraft can operate simultaneously from different ships. For instance, Figure 35 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.

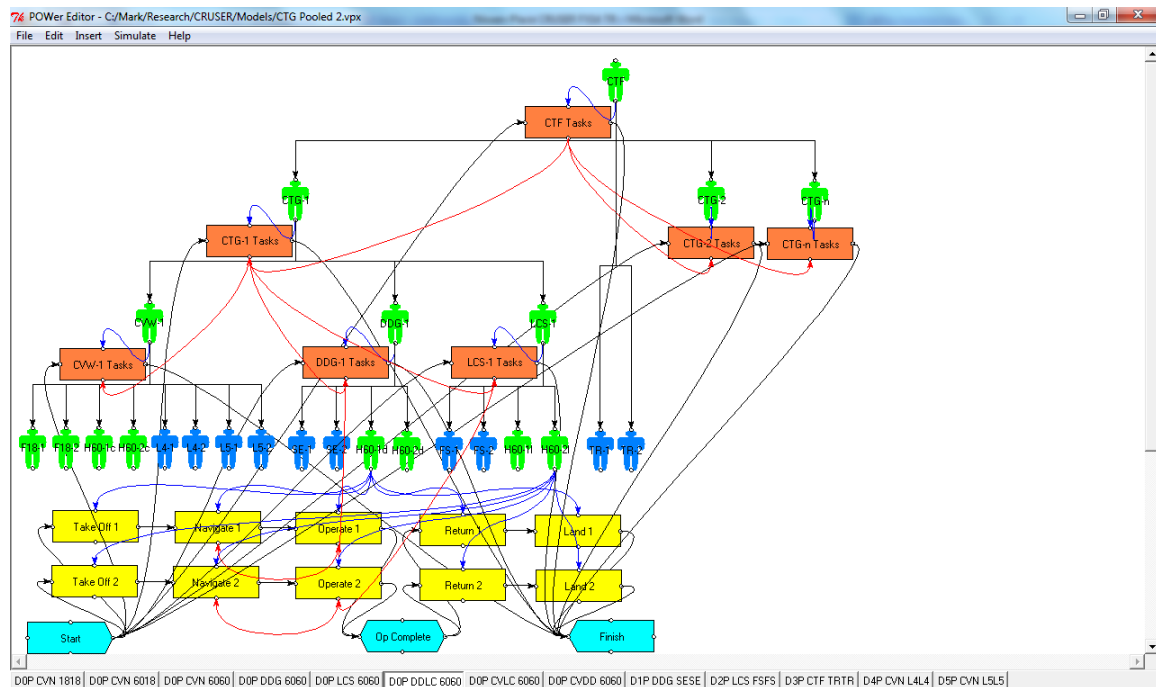


Figure 35 Baseline Model (D0P) – DDG MH-60 & LCS MH-60

Hence our D0P experiment condition includes eight¹⁴ 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 19.

¹⁴ 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 19 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 attention¹⁵. We include a screenshot for this model in Figure 36.

¹⁵ 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.

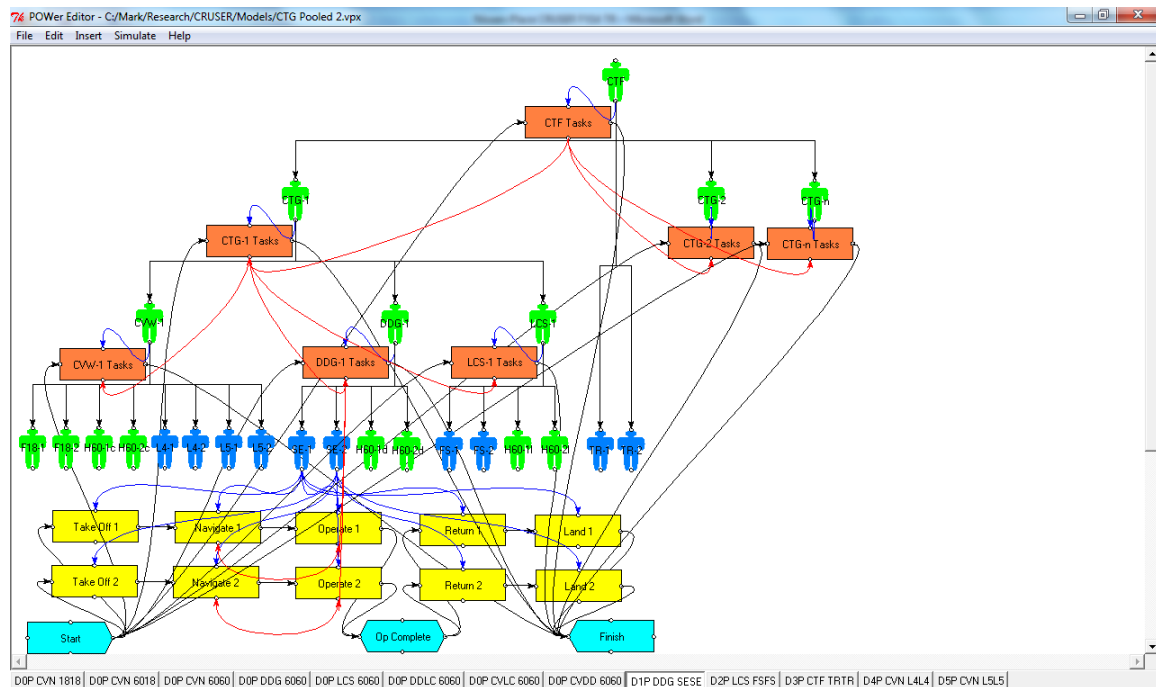


Figure 36 Model D1P – DDG ScanEagles

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 37.

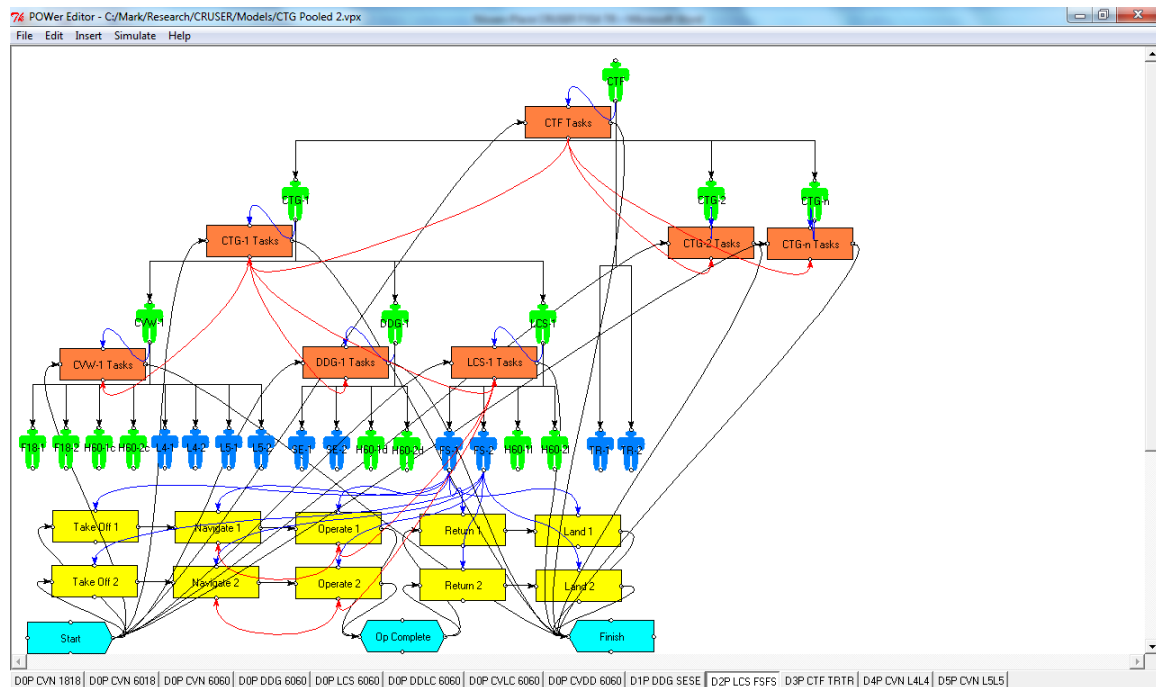


Figure 37 Model D2P – LCS FireScouts

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 38.

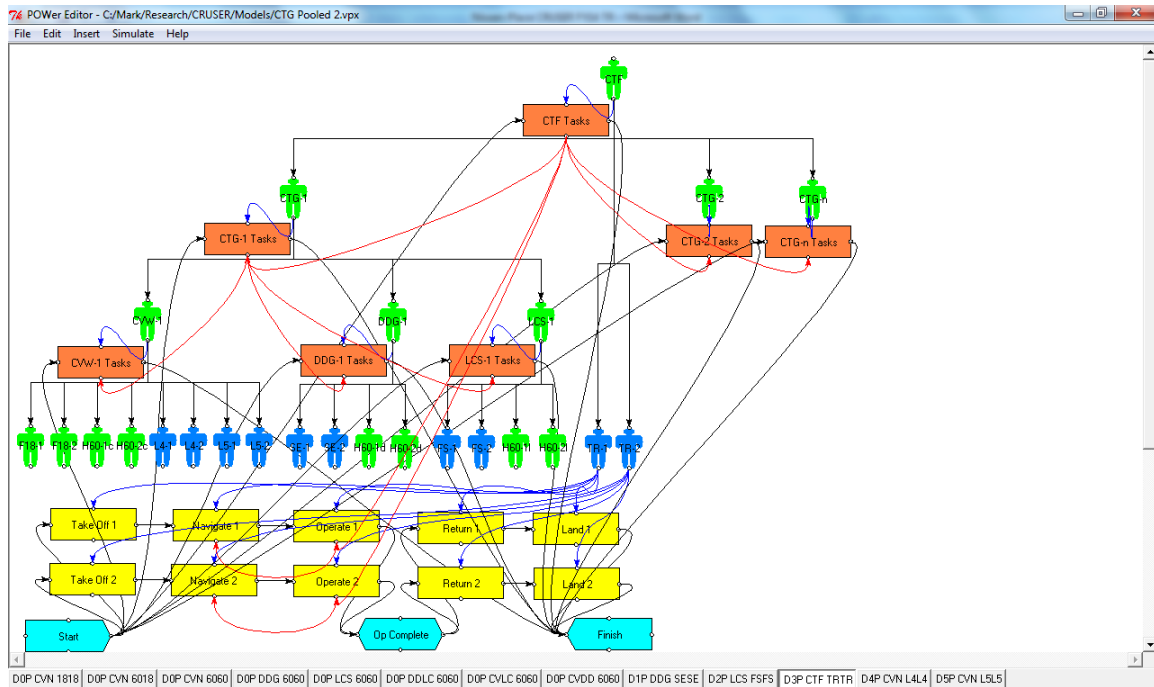


Figure 38 Model D3P – Tritons

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 model¹⁶. We include a screenshot for this model in Figure 39.

¹⁶ Some model iterations representing integrated interdependence include L4 and L5 UAVs operating from other ship platforms. We describe these in their corresponding sections below.

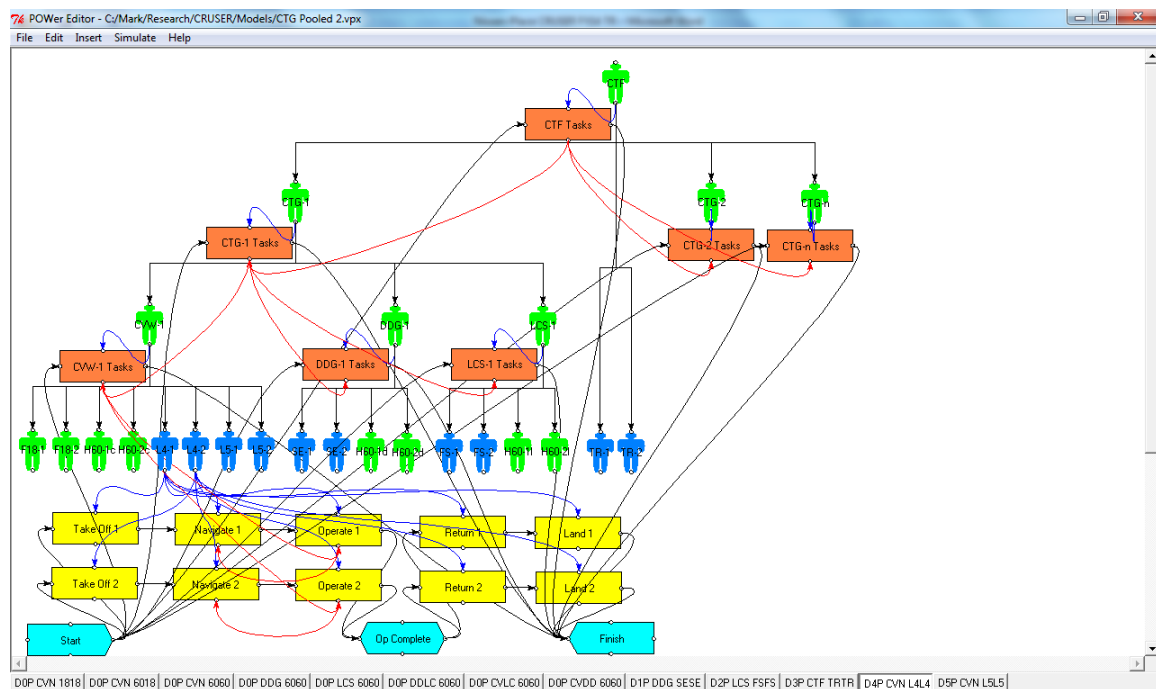


Figure 39 Model D4P – L4 UAVs

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 40.

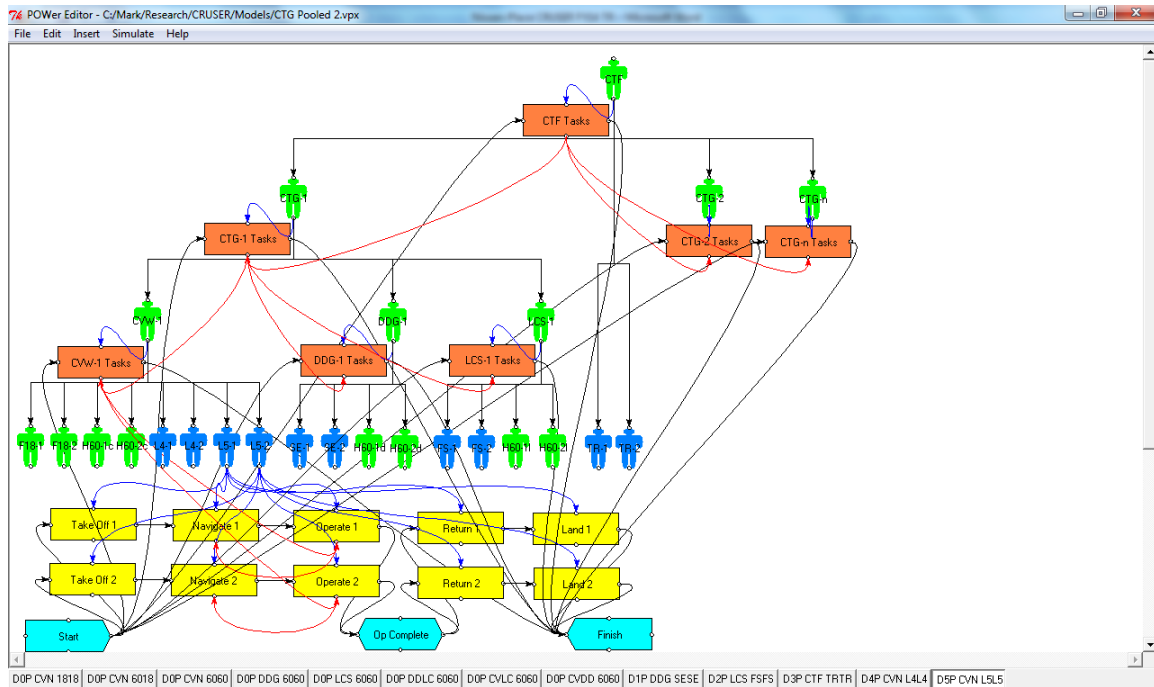


Figure 40 Model D5P – L5 UAVs

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 41.

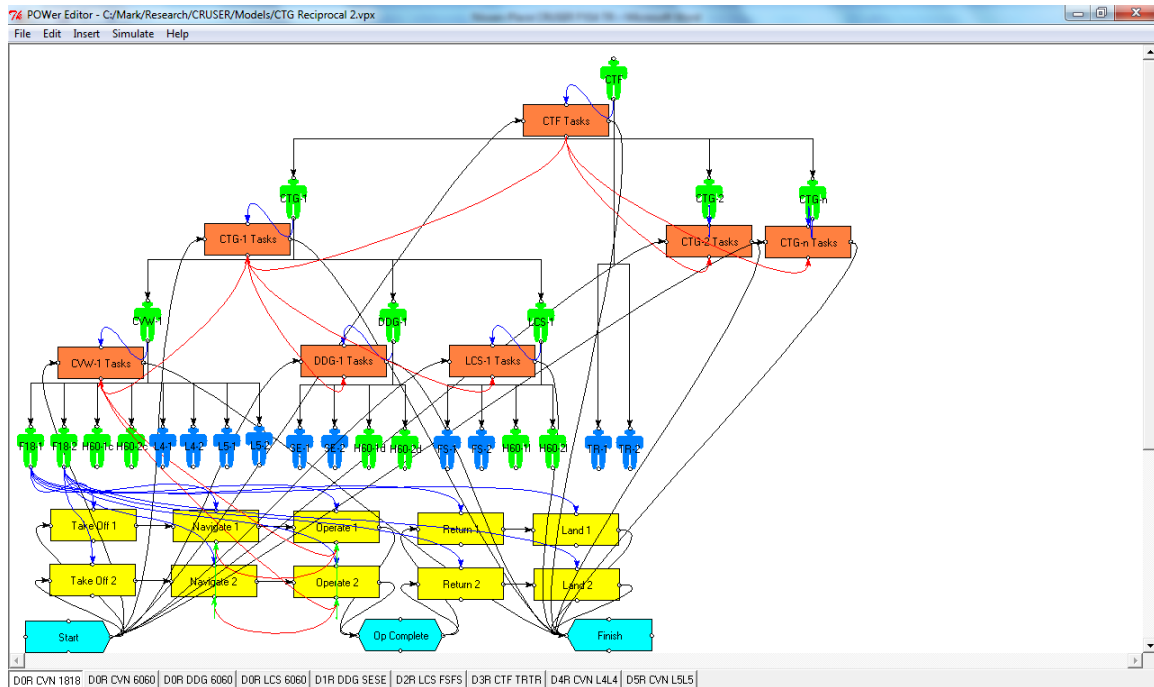


Figure 41 Model D0R – CVN F/A-18s

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 aircrews¹⁷ (onboard ship). We include a screenshot for this model in Figure 42.

¹⁷ 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 today.

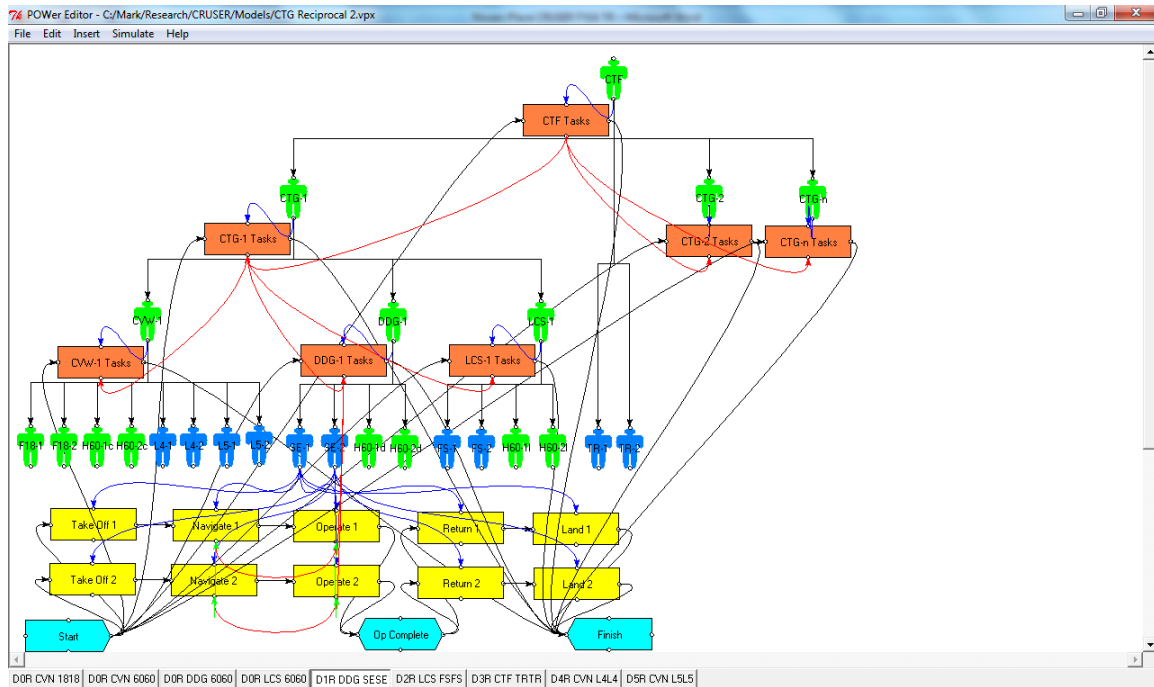


Figure 42 Model D1R – DDG ScanEagles

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 aircrews¹⁸ (onboard ship). We include a screenshot for this model in Figure 43.

¹⁸ 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 today.

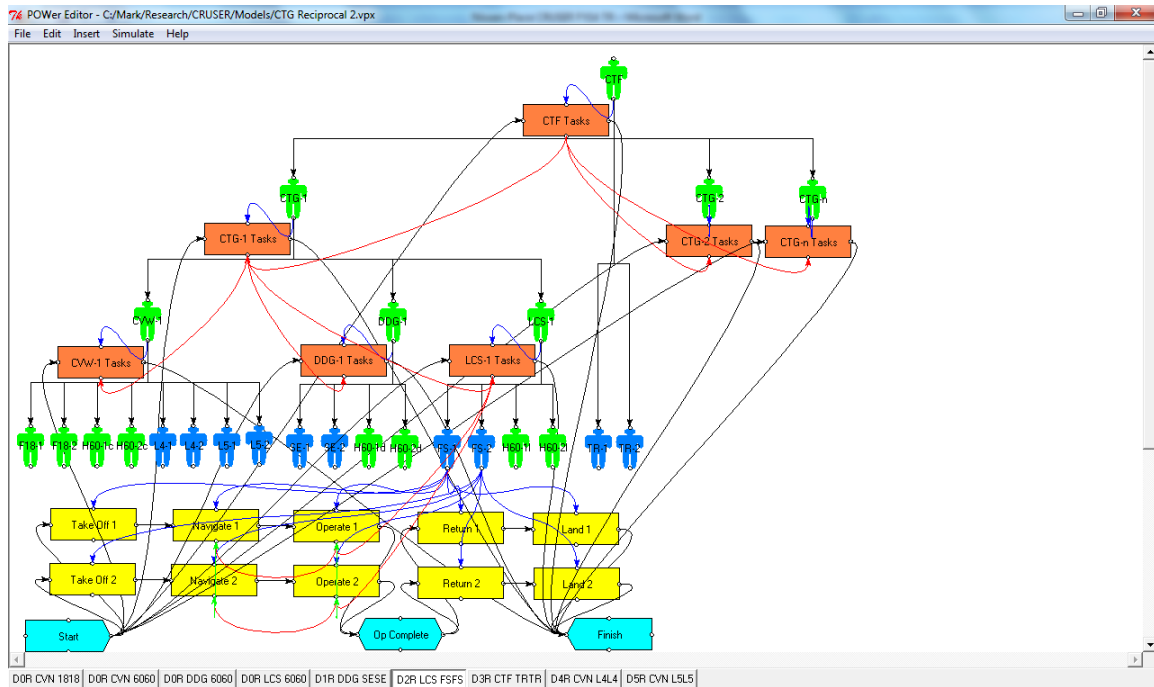


Figure 43 Model D2R – LCS FireScouts

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 aircrews¹⁹ (on land). We include a screenshot for this model in Figure 44.

¹⁹ 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 today.

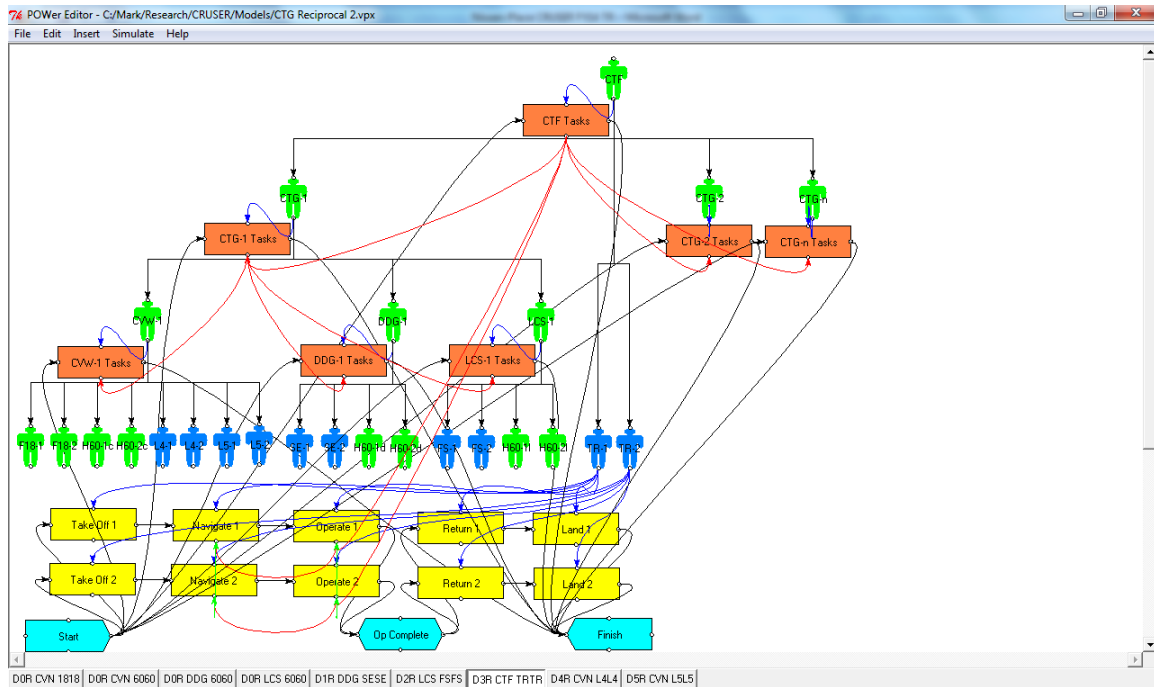


Figure 44 Model D3R – Tritons

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 practice²⁰. We include a screenshot for this model in Figure 45.

²⁰ We presume this UAV’s ability to sense other aircraft in flight. Remote aircrews are not required to accomplish such sensing.

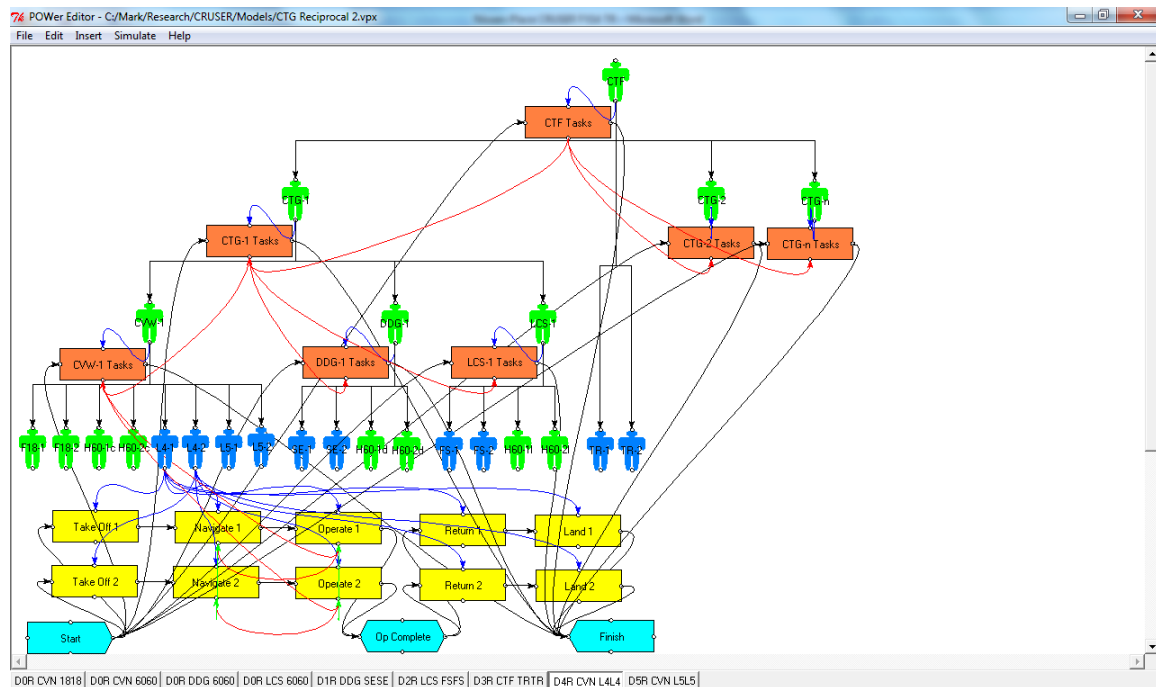


Figure 45 Model D4R – L4 UAVs

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 practice²¹. We include a screenshot for this model in Figure 46.

²¹ We presume this UAV’s ability to sense other aircraft in flight. Remote aircrews are not required to accomplish such sensing.

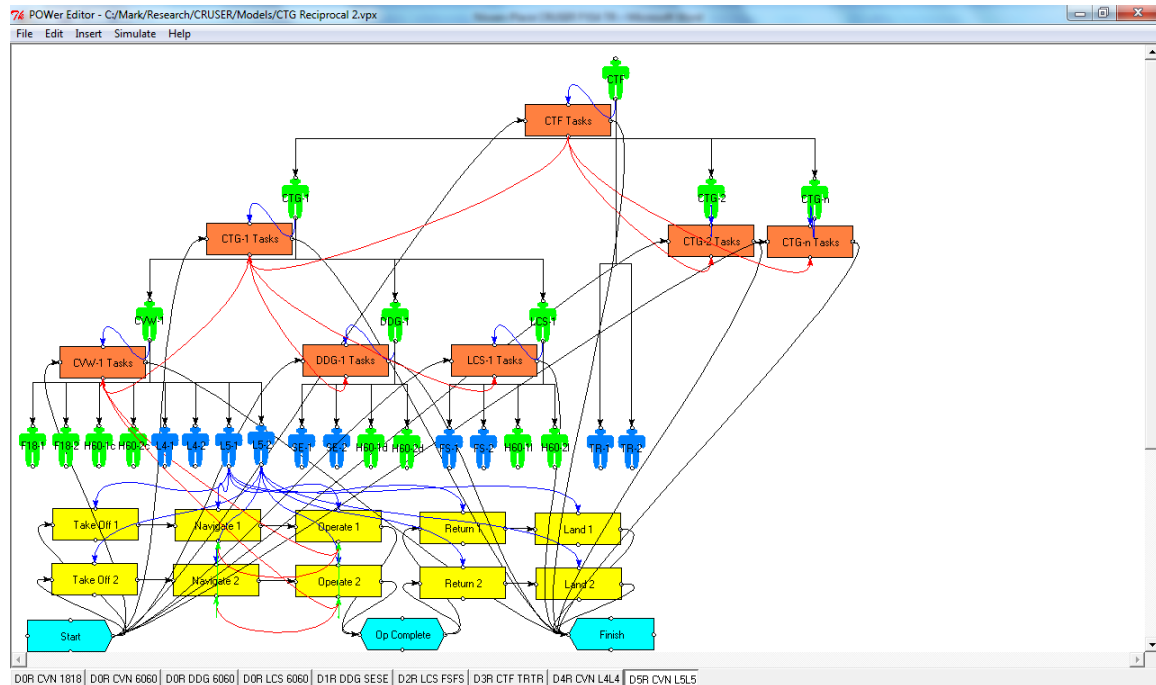


Figure 46 Model D5R – L5 UAVs

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 demands²².

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 47.

²² Such demands are likely to be organizational and cultural in addition to technical.

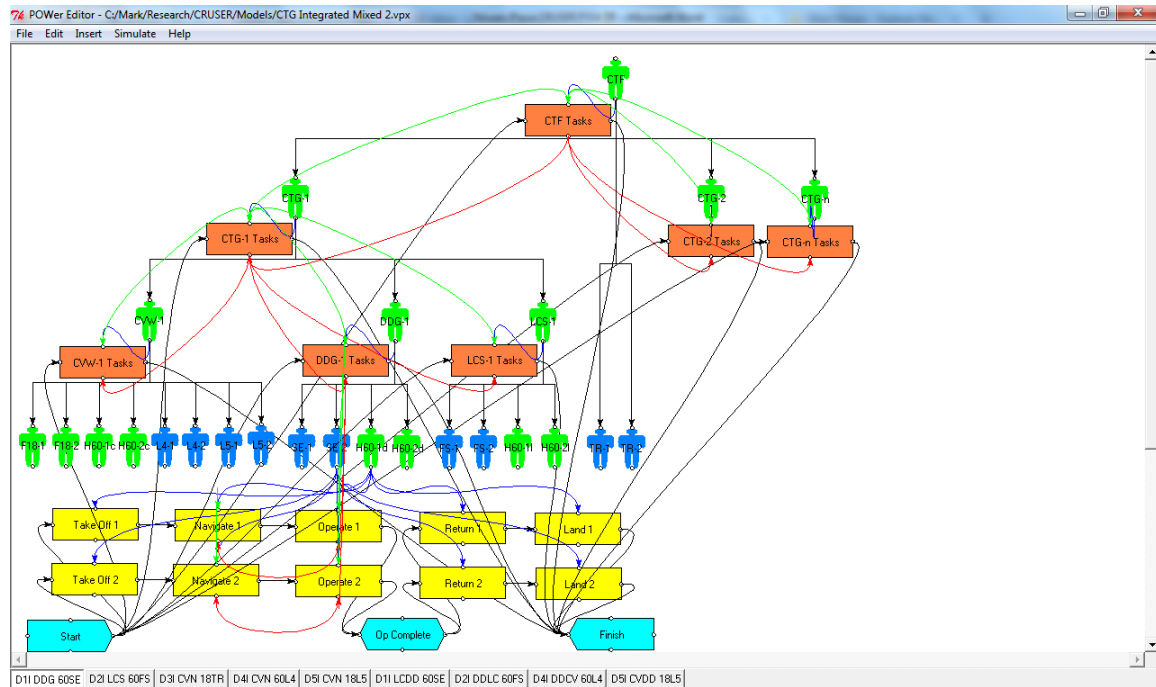


Figure 47 Model D1I – DDG MH-60 & ScanEagle

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 demands²³, 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 48.

²³ Such demands are likely to be organizational and cultural in addition to technical.

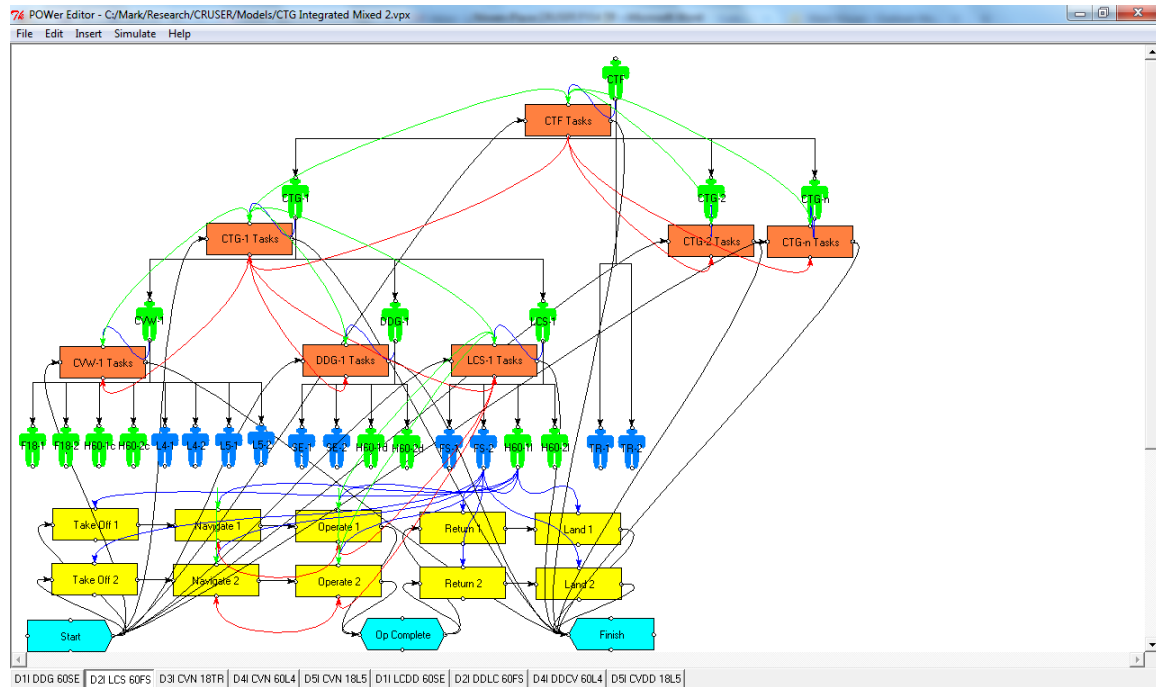


Figure 48 Model D2I – LCS MH-60 & FireScout

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 demands²⁴, 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 49.

²⁴ Such demands are likely to be organizational and cultural in addition to technical.

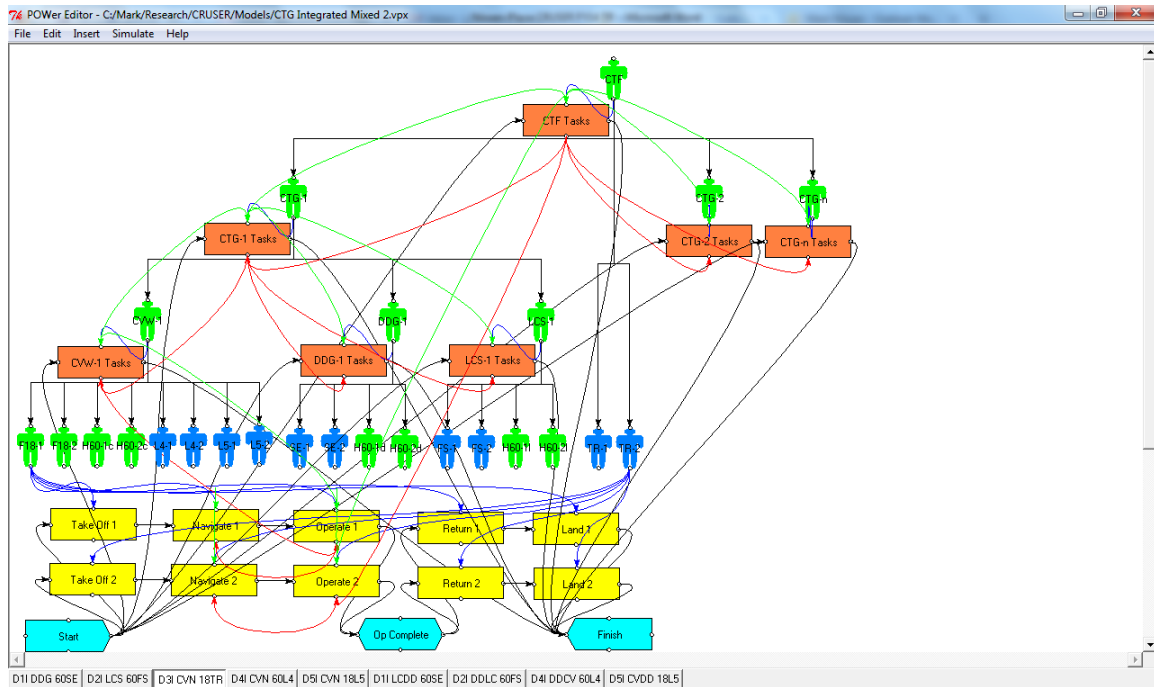


Figure 49 Model D3I – F/A-18 & Triton

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 demands²⁵, 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 50.

²⁵ Such demands are likely to be organizational and cultural in addition to technical.

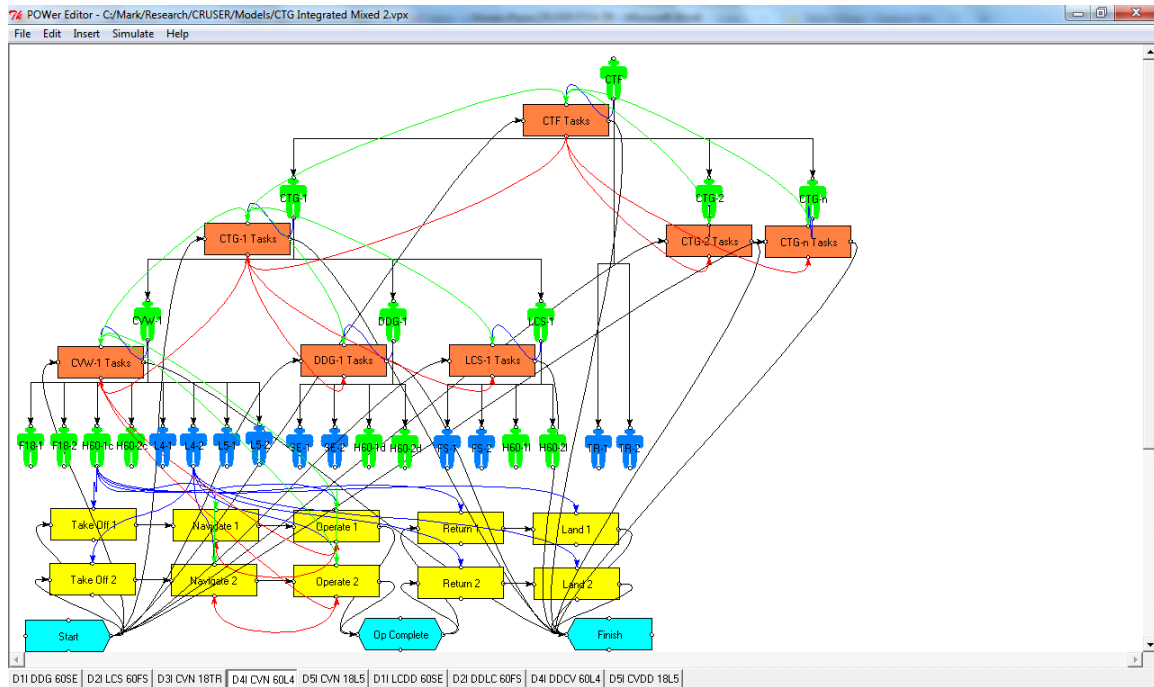


Figure 50 Model D4I – MH-60 & L4 UAV

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 demands²⁶, 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 51.

²⁶ Such demands are likely to be organizational and cultural in addition to technical.

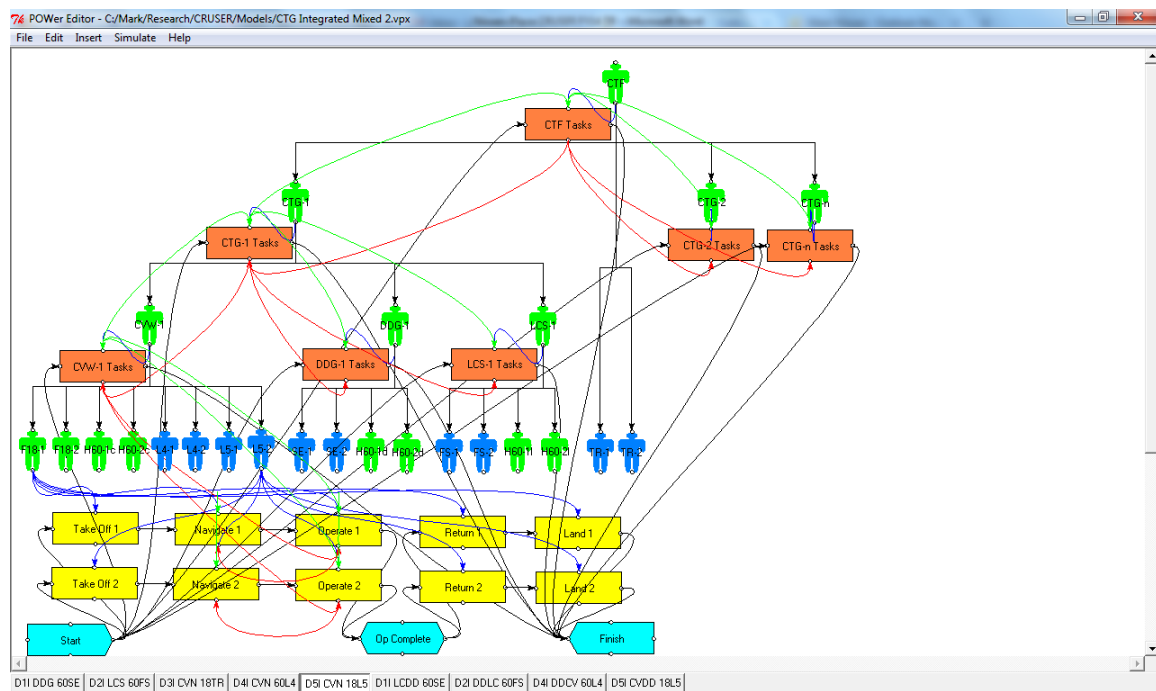


Figure 51 Model D5I – F/A-18 & L5 UAV

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California 93943
3. Research Sponsored Programs Office, Code 41
Naval Postgraduate School
Monterey, CA 93943
4. Dr. Raymond Buettner
CRUSER Director
Naval Postgraduate School
Monterey, CA 93943
5. Dr. Dan Boger
IS Department Chair
Naval Postgraduate School
Monterey, CA 93943