INSTITUTE FOR DEFENSE ANALYSES

NSD-5040

Coping with Degraded or Denied Environments in the C2 Approach Space

François Bernier, Ph.D, Defence Canada—Valcartier
Kevin Chan, Ph.D, U.S. Army Research Laboratory
David S. Alberts
Paul Pearce, Ph.D. Defence Science and Technology Laboratory

October 2013

Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

IDA Log No. H 13-001445

The Institute for Defense Analyses is a non-profit corporation that operates three federally funded research and development centers to provide objective analyses of national security issues, particularly those requiring scientific and technical expertise, and conduct related research on other national challenges.

About This Publication

This work was conducted by the Institute for Defense Analyses (IDA) under contract DASW01-04-C-0003, Task AA-6-3630, "DoD Command and Control Research Program (DoD CCRP) Support," performed for the Command and Control (C2) Programs and Policy Directorate, Office of the Under Secretary of Defense for Acquisition, Technology & Logistics, (AT&L). The views, opinions, and findings should not be construed as representing the official position of either the Department of Defense or the sponsoring organization.

4850 Mark Center Drive, Alexandria, Virginia 22311-1882 • (703) 845-2000.

NSD-5040

Coping with Degraded or Denied Environments in the C2 Approach Space

François Bernier, Ph.D, Defence Canada—Valcartier
Kevin Chan, Ph.D, U.S. Army Research Laboratory
David S. Alberts
Paul Pearce, Ph.D. Defence Science and Technology Laboratory

October 2013

18th ICCRTS

Coping with Degraded or Denied Environments in the C2 Approach Space

Paper #066

Topic(s)
Topic 1: Concepts, Theory, and Policy

Name of Author(s)

François Bernier, Ph.D.
Defence R&D Canada – Valcartier
2459 blvd. Pie-XI North
Quebec, QC, G3J 1X5
Canada
francois.bernier@drdc-rddc.gc.ca
+1 418 844 4000

Kevin Chan, Ph.D.
US Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD, 20783
USA
kevin.s.chan@us.army.mil
+1 301 394 5640

David S. Alberts, Ph.D.
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA, 22311
USA
dalberts@ida.org
+1 703 845 2411

Paul Pearce, Ph. D.
Defence Science and Technology Laboratory
Fort Halstead,
Sevenoaks, Kent, TN14 7BP
United Kingdom
pvpearce@dstl.gov.uk
+44 01959 89 2087

Point of Contact

Kevin Chan
kevin.s.chan@us.army.mil
+1 301 394 5640

Coping with Degraded or Denied Environments in the C2 Approach Space

Abstract

The NATO Network Enabled Operations (NEC) C2 Maturity Model (N2C2M2) defines a number of command and control (C2) Approaches that correspond to various ways to accomplish C2 functions. These Approaches are defined by organizational the allocation of decision rights, patterns of interaction, and the distribution of information. Recent work in C2 theory has considered the differences in performance relative to the C2 Approach that is adopted. This work has investigated the idea that an optimal operating region of the C2 Approach Space can be identified for particular missions and circumstances, where optimal is a function of effectiveness, efficiency and agility. While circumstances that are characterized by the presence of degraded network conditions or hostile or extreme environments is of great interest, the performance of various c2 Approach options under these conditions have not been well studied. This paper focuses on the relative resilience of organizations as a function of their C2 Approach (a key component of agility). We explore the relationship between C2 Approach and performance under degraded information and communications environments using a set of six unique simulation experiments.

1 Introduction

Command and control (C2) must occur in a wide variety of tactical environments. Most importantly, organizations must be capable of maintaining performance in situations where the operating environment is far from ideal. From a force agility perspective, it is desirable that the organization is able to maintain a satisfactory level of performance despite any challenges presented by the environment, in this case a degraded information and communications environment. For example the Army Field Manual (FM 6-0) Mission Command: Command and Control of Army Forces (2011) includes verbiage about techniques tactics and procedures in how to perform their mission when “interactions are often unpredictable—and perhaps uncontrollable.” The Navy Warfare Development Command (NWDC) released a tactical memorandum (TACMEMO) on Command and Control in a Denied or Degraded Environment (C2D2E) (US Navy, 2012). In terms of training exercises, there is growing awareness that commanders and their organizations must be exposed to such environments[1]. The Chairman of the Joint Chiefs of Staff summarizes this awareness by saying that the joint forces "must grow capabilities that enable operations when a common domain is unusable or inaccessible,” in the 2011 National Military Strategy. The community of cyber warfare also recognizes the importance of ensuring unhindered operations in degraded cyber environment (Rickards, 2010).

The need to study agility, mission performance or other organizational performance metrics in the presence of hostile or adverse entities or conditions resulting in degraded and denied operational environments has been a common theme across contemporary C2 research. Specifically, the focus is on adversarial entities attempting to hamper or disrupt the communications infrastructure and operations in urban environments, which introduce RF communication issues along with social and cultural understanding / counterinsurgency (COIN) issues. This paper investigates the impact that denied or degraded environments have on the performance of these organizations. We look at this problem from the perspective of adopting various C2 Approaches and other capabilities dictated by specific organizational design parameters. This work is a partial representation of the NATO Research Group SAS-085, which has conducted a meta-analysis based on a series on simulation-based experiments to study C2 Agility.

2 Background

The SAS-085 NATO Research Task Group (RTG) on Command and Control (C2) Agility and Requisite Maturity was created with the objective of improving the understanding of C2 agility for NATO and its member nations. The work on C2 agility presented in this paper is part of a group of experiments conducted by members of SAS-085 and their organizations.

2.1 C2 Approach Space

The NATO Network Enabled Operations (NEC) C2 Maturity Model (N2C2M2) developed by NATO SAS-065 and published by the DoD CCRP (Alberts, Huber, & Moffat, 2010), defines a number of C2 Approaches that correspond to various ways to accomplish C2 functions. These Approaches differ on at least three major aspects of an Approach to C2: the allocation of decision rights (ADR), the pattern of

[1] Source: http://www.af.mil/news/story.asp?id=123241938

interaction among entities (PoI), and, distribution of information among entities (DoI), in a collective endeavor. These and many other C2 Approaches can be graphically represented in the three-dimensional C2 Approach Space illustrated in Figure 1.

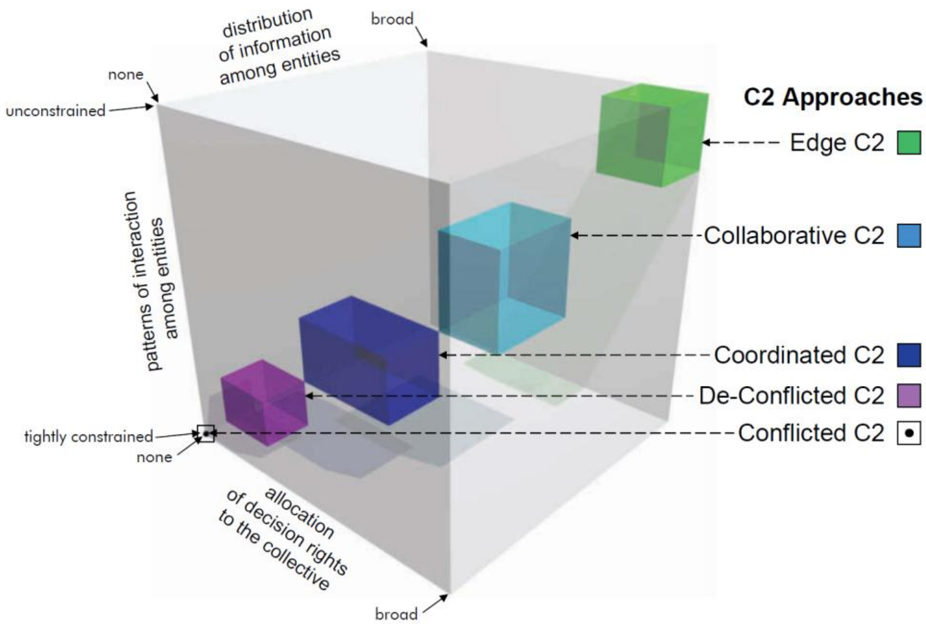

Figure 1: C2 Approaches represented in the C2 Approaches Space (from Alberts et al. (2010)).

As an entity or collective moves in the C2 Approach Space from the left, bottom, back of the cube (Conflicted) to its opposite corner (Edge), the C2 Approaches that are adopted are increasingly network-enabled. The predecessor to SAS-085, SAS-065, hypothesized that more network-enabled C2 Approaches would be more versatile, that is, they would be able to succeed under a wider variety of circumstances than less network-enabled Approaches, particularly in dynamic situations that are characterized by high degrees of uncertainty and complexity. SAS-085 has, as part of its work program, designed and conducted two meta-analyses, one for a series of case studies and another one for series of simulation-based experiments, to explore a set of hypotheses that involve the relationship between C2 Approaches, Agility, the C2 Approach Space and C2 Agility. This paper presents the results of a subset of the findings of the experiments that have been conducted and analyzed to date focusing upon the impact of degraded information and communications capabilities.

2.2 Agility vs. C2 Agility

Given the lack of precision in the every-day language associated with agility, we define and distinguish Agility and C2 Agility. SAS-085 sees Agility in two ways; as both an ‘outcome’, and as a ‘capability’ and provides a way of observing and measuring each. Agility as an ‘outcome’ can be observed when an entity manifests agile or, in some case, when an entity fails to manifest agility. Agility as a ‘capability’ represents a potential; measuring it requires an understanding of the characteristics, attributes, and behaviors that either enable or inhibit agility. The capability referred to as agility is defined by SAS-085 as “Agility is the capability to successfully effect, cope with and/or exploit changes in circumstances.” Where “Successfully” is defined as operating within acceptable bounds. This includes defining the significance of “out of bounds performance” as a function of both magnitude (how far) and duration (how long). Changes in circumstances (CiCs) imply a current or normal state (baseline) and include both changes to the State of the Environment (including other entities) and/or to the State of Self. These changes are not restricted to the physical domain, but also include changes to variables in the Information, Cognitive, and Social domains as well. The outcome, referred to as agility, is captured by a measure that is calculated by determining the portion of the Endeavor Space where an entity can successfully operate, where Endeavor Space is the set of possible circumstances.

C2 Agility is the set of capabilities and behaviors that enable an entity to successfully accomplish C2 functions over an Endeavor Space. An entity's C2 Agility is related to the range of C2 Approach options an entity can adopt, its ability to select or adopt the most appropriate approach from this set, given the mission and circumstances, and the versatility of its C2 Approach options. The greater the variety of C2 Approaches in an entity's tool kit, the greater the entity's potential C2 Agility. Given the complexity and dynamics of the environment in which an entity will be operating, C2 Agility is also a function of an entity's ability to recognize when significant changes in circumstances occur and, if necessary, a transition to a different one of its C2 Approaches. SAS-065 introduced the term C2 Maturity to describe entities that were 1) capable of adopting more networked- enabled C2 Approaches and 2) were also able to less included network-enabled C2 Approaches. These entities were able to position themselves anywhere in the C2 Approach Space that was closer to the origin than the more network-enabled C2 Approach in their tool kit.

It should be noted that a C2 organization might design their organization to operate in a specific region of this C2 Approach Space; however, it is possible that the actual parameters in which the organization is operating differs from its intentions. Through the simulation experiments, we are able to characterize this difference (designed C2 operating point vs. actual operating point).

2.3 Degraded and Denied Environments

Operational environments will not be pristine and organizations may not be able to operate with the normal (baseline) assumptions. Any state of the environment in which the organization operates without its full complement of information and communications capabilities is considered to be degraded or denied. There is a distinction between degraded capabilities that result from adversarial actions and environmental conditions and those that are 'self-inflicted.' In this paper, we are looking at the impact from adversarial actions and environmental conditions. We assume that Self CiCs do not contribute to a degraded or denied environment, but similarly degrade the performance of organizations.

SAS-085 observed that one needs to make a distinction between the designed C2 operating point (the intended C2 Approach) and the actual operating point in the C2 Approach Space. Where one is located or positioned in the C2 Approach Space depends on the operating conditions. For instance, even if an organization defines itself as having adopted a collaborative to C2, a highly destructive attack to its communication infrastructure will deny this entity the ability to operate as collaboratively. More discussion about the desired and actual position in the C2 Approach Space is provided in (Alberts, Bernier, Chan, & Manso, 2013). Our analysis looks at a set of C2 Approach options and the ability of each of these Approaches to deal with (maintain performance) degraded environments. That is, we observe 'involuntary' movement or changes in position in the C2 Approach Space that are caused by denied or degraded environments.

Another paper that reports on SAS-085 experiments looks at the benefits of being able to adopt more than one C2 Approach given not only for conditions that involved degraded and denied environments, but also those that create a variety of other stresses. Results reported in this paper suggested the existence of a mediator variable[2], likely the initial positioning of the organization in the C2 Approach Space, that affects the relationship between a given C2 Approach and performance. In this paper we consider the following questions: What is the relationship between the actual location in the C2 Approach Space and entity agility? Do entities that adopt more networked C2 Approaches remain closer to their intended position the C2 Approach Space? If so, why? In the next section, we formally introduce our hypothesis.

3 Experimental Design

3.1 Overview

In order to produce more complete, robust and generalizable set of findings SAS-085 undertook a prospective meta-analysis consisting of commonly design runs utilizing multiple experimental platforms and venues. Specifically, SAS-085 members from five NATO member nations, namely USA, Portugal, Canada, United Kingdom, and Italy jointly conceived and conducted a series of experiments using multiple platforms and venues. Together they defined a set of common research hypotheses and identified a comparable independent and dependent variables. Each researcher implemented these measures a bit differently and conducted a set of runs using a different model or instantiation. The benefits of conducting a simulation-based meta-analysis are numerous: findings can be generalized to a broader range of contexts; between-experiment variation can be controlled; statistical power is improved; and, the influence of local biases is reduced. Bernier et al. (2013) presents the methodology and discusses the challenges of such meta-analysis. The individual experiments did not conducted any analysis themselves but instead reported all data into single compendium to be analyzed jointly in the meta-analysis.

3.2 Hypotheses

The first hypothesis tested by the meta-analysis was "more network-enabled C2 Approaches exhibit more agility" (Bernier, Alberts, & Manso, 2013). The effort to test this hypothesis raises other questions that this paper tries to answer. This paper starts by exploring the consequences of degraded conditions on the position of an entity in the C2 Approach Space. Then, it investigates the impact of the position in the C2 Approach Space on agility. Three hypotheses are investigated.

- H1: Entities operating in more network-enabled C2 Approaches can maintain a better:
  - H1.1 relative location (relative to the non-degraded condition)in the C2 Approach Space; and
  - H1.2 global location in the C2 Approach Space.
- H2: The position in the C2 Approach Space is positively correlated with agility.

[2] A mediator variable is a third explanatory variable (e.g., location in the C2 Approach Space) that explains the mechanism that underlies an observed relationship between an independent (e.g., *C2 Approach*) and a dependent variable (e.g., *Agility Score*).

3.3 Design

Figure 2 illustrates the experimental design of the prospective meta-analysis that involves two explicit independent variables and one implicit independent variable. The first independent variable, *C2 Approach*, can take on five different values (Conflicted, De-Conflicted, Coordinated, Collaborative, or Edge). A single experiment (set of runs) instantiates from two to all five of the pre-defined C2 Approaches. Verifications were made to ensure that these C2 Approaches were equivalent across all experiments. Two of these instantiations were judged as too dissimilar and were dropped. The second independent variable, *Endeavor Space* represents a series of challenges and conditions, each of which could occur in any given C2 Approach. The endeavor space includes various states of degraded and denied environments as well as other challenges that cause effects similar to a degraded environment. Each experiment employed a different endeavor space. Finally, *Experiment* is an implicit independent variable. It is of little interest in itself but is nevertheless captured because it represents a sample of a virtually infinite population of experiments that do not all exist yet but that could be created with the same purpose. This way, findings with these six experiments can be generalized to an infinite number of experiments that could be created in a similar fashion and for the kind of studies. The six experiments used for this experiment are IMAGE (Lizotte, Bernier, Mokhtari, & Boivin, 2013), WISE (Pearce, Robinson, & Wright, 2003), PANOPEA (Bruzzone, Tremori, & Merkuryev, 2011) and three variants of ELICIT (Chan, Cho, & Adali, 2012; Manso & Nunes, 2008; Ruddy, 2007).

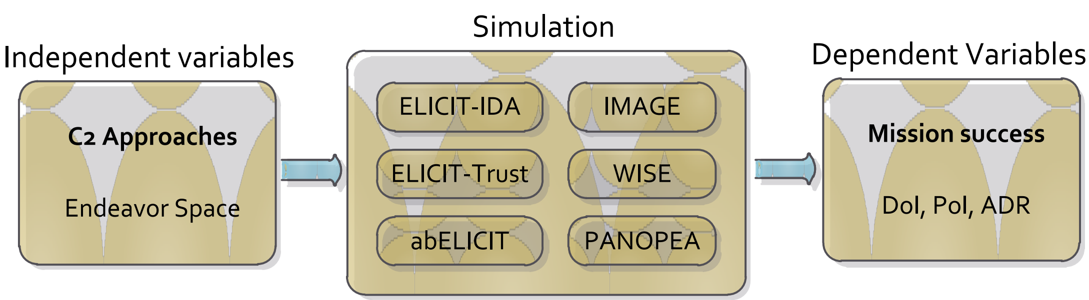

Figure 2: Experimental design.

Each experiment defines a unique endeavor space that comprises up to 100 challenges, also called changes in circumstances (CiCs). Some CiCs represent degraded/extreme environments or various degrees of situational complexity or dynamics, situations that a collective may have to overcome to succeed in its mission. The primary role of the endeavor space is to deduce agility via the agility score, i.e., the proportion of the endeavor space where a collective is successful. But it serves two additional purposes. First, the endeavor space corresponds to what is called a *noise factor* in the literature (Steinberg & Bursztyn, 1998). Such factors aim at recreating the natural variability found in the real-world and then at improving the external validity and robustness of the findings. Second, incorporating a large quantity of CiCs reduces the probability of selecting only CiCs that would be systematically detrimental or beneficial to some C2 Approaches (law of large numbers). Between two and five types (e.g., network latency and trust) of CiCs were included for each experiment. The resulting endeavor spaces were then populated by performing all possible combinations of the possible values (e.g., low/high latency x low/high trust) for all these types of CiCs.

Four dependent variables (DVs) were measured for each run. The first DV, *Mission success*, is a normalized value representing the success or failure of the mission and is an intermediate variable used to calculate agility. The agility of a collective operating under a given C2 Approach was measured by the proportion of the endeavor space (or proportion of CiCs) in which a collective is successful. This value is called the *Agility Score* and is calculated by averaging all values of *Mission Success* measured for all CiCs simulated for a given C2 Approach. The next three DVs are metrics that estimate the actual position of a collective in the C2 Approach Space, when exposed to a specific CiC, while operating according to a given C2 Approach. The actual measure is aimed at determining if a collective is able to maintain its intended position within the C2 Approach Space and measures the degree of difference from the intended position. For instance, even if a collective's intent is to establish a broad DoI, degraded conditions on the infrastructure may prevent the collective from communicating properly, thereby perturbing the intent of the collective. This would result in the DoI actually being much lower than the one intended. The same principle also applies for PoI. As for ADR, experience revealed that this dimension (or at least the metric used to represent it) is not influenced by degraded conditions (CiCs) and that ADR can be considered to be more policy based and therefore for the experiments can be considered to be fixed for a given instantiation of a C2 Approach. The danger with fixing the ADR is the ADR may not be in phase with changes in DoI and/or PoI, leading to inappropriate ADR policy in some situations. Additional discussion about a collective intended and actual position in the C2 Approach Space is available in (Alberts et al., 2013).

This experiment exploits blocking in its design. Each *Experiment* is a block of homogenous experimental units; DVs are more alike within an experiment than among experiments, that is, values within an experiment are not independent of each other. The current experimental must deal with two sources of randomness. The first source is produced by the designers of each experiment that "randomly sampled" a subset of CiC/degraded conditions from a virtually infinite endeavor space when they created their endeavor space. The second source is the experiment itself, which consists of samples of an infinite number of possible experiments with similar purposes and hypotheses. Both random variables will cause DoI, PoI and ADR to be distributed over a broad range of values. An example of consequence is that simply comparing mean values of DoI for two C2 Approaches would not have been sufficient for claiming that one value was higher than another, i.e., that they were located in different regions of the C2 Approach Space; since the difference might be due to randomness during the "sampling", hypotheses were tested with an analysis of variance using a mixed effect model (*Experiment* was the random variable and *C2 Approach* the fixed effect). To reiterate, a set of simulation runs were conducted by each nation according to a common experimental plan. Then, these data were merged in the meta-analysis.

4 Results

The following section gives an overview of the experimental data. The three subsequent sections present the results of the analyses related to each of the three hypotheses.

4.1 Overview

Figure 3 depicts the observed positions in the C2 Approach space for each of the simulation runs (values of ADR, PoI, and DoI for each of the six experiments, the C2 Approaches and CiCs instantiated in each experiment that includes the baseline and a number of degraded conditions). A first noteworthy observation is that the positions in the C2 Approach Space for each of the C2 Approach differ among the experiments. In addition, the relative spread (size of the region covered by a given C2 Approach) also varies considerably. The specific nature of the mission executed under each experiment explains, in large part, these observed differences. Such variation is not bad in itself because it represents the diversity of situations taken into account in this meta-analysis. Nevertheless, these differences had to be accounted for in the statistical models (mixed linear model) to improve statistical significance.

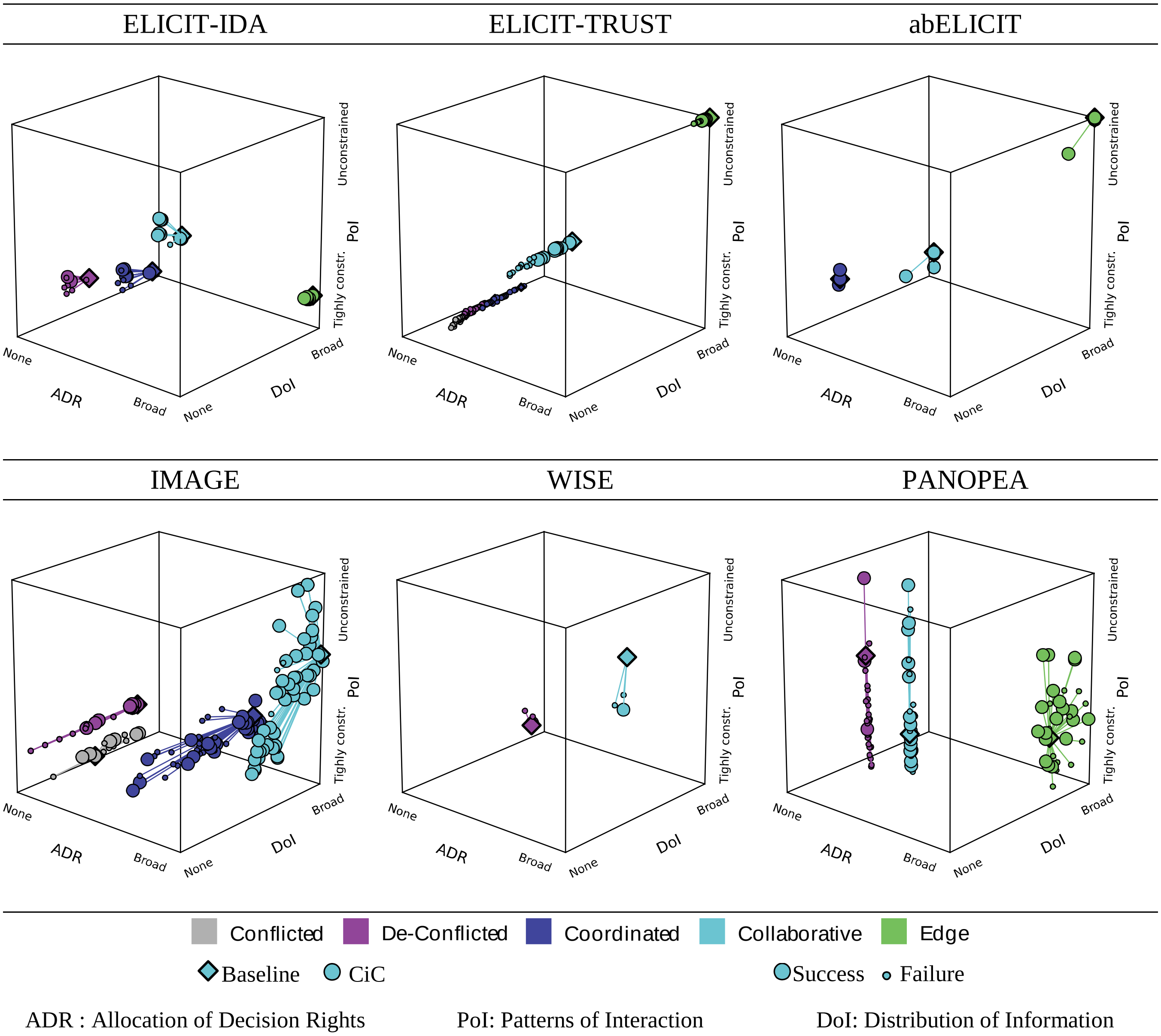

Figure 3: Tri-dimensional mapping of the endeavour space (CiCs) into the C2 Approach Space.

4.2 H1.1: Relative Position in the C2 Approach Space

The first hypothesis that was examined (H1.1) was "Are more network-enabled C2 Approaches able to maintain their baseline/non-degraded condition relative position in the C2 Approach Space better than less network-enabled Approaches? Since none of the experiments involved any changes to ADR, only

PoI and DoI was affected. Consequently, a measure of spreading of the CiCs was calculated by the area occupied by all CiCs in the DoI-PoI plane for each C2 Approach and experiment. A convex-hull was built for each set of CiCs based on Andrew's monotone chain algorithm (Andrew, 1979) that computes the smaller convex set that contain all CiCs. The area of the resulting polygon was computed based on the Green's theorem that sums the cross product around each vertex part of the polygon.

Figure 4 shows the location of the CiCs in the DoI-PoI plane and the computed convex hull for each C2 Approach in each experiment. Although one might be tempted to claim that some C2 Approaches occupy a smaller region this conclusion would not be a valid one. This is because the points used to compute the average are randomly distributed (because of the two random independent variables explained in Section 3.3) and randomness in the selection of those independent variables (improper selection of the degraded conditions) may explain the observed results.

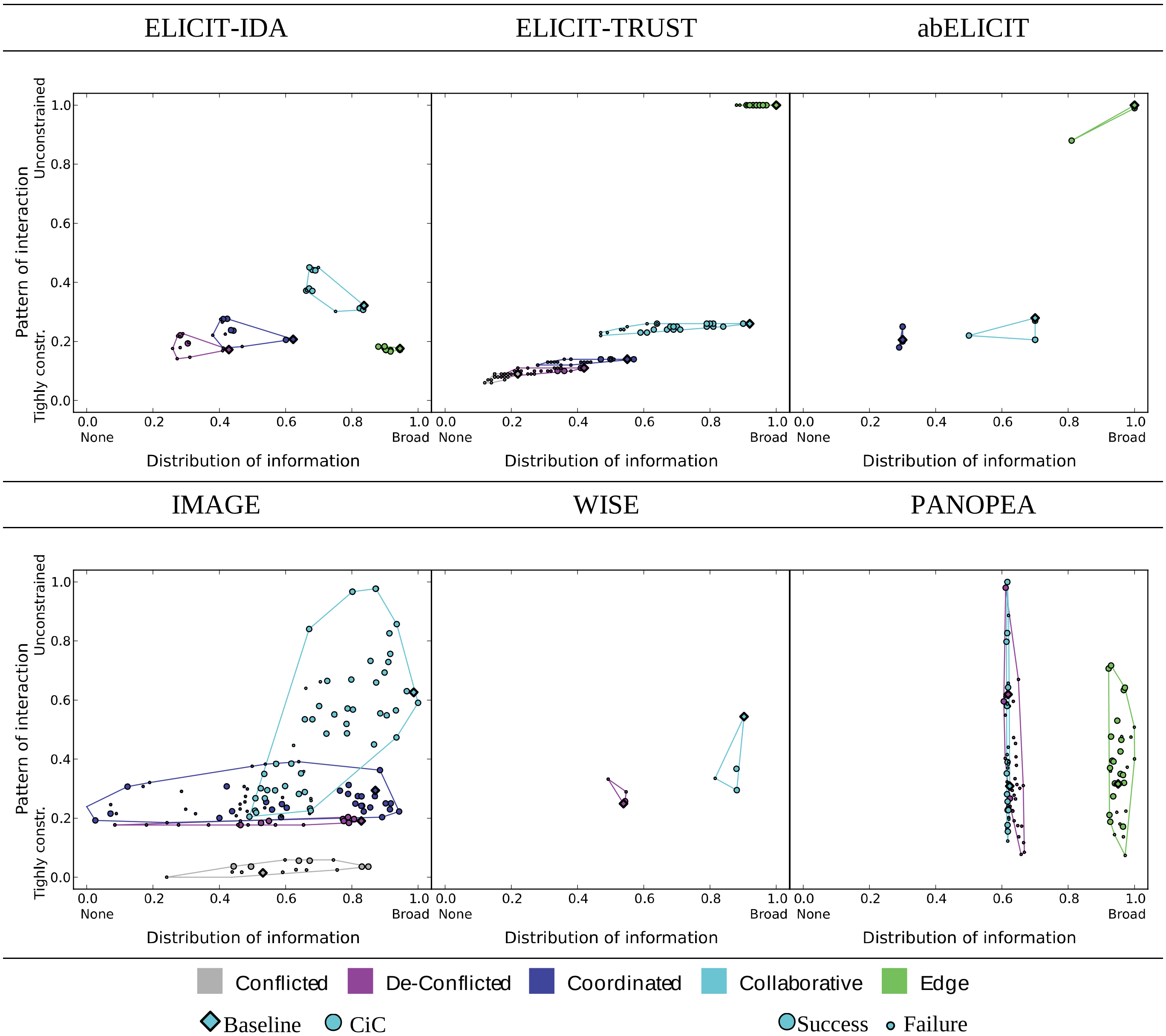

Figure 4: Spreading in the DoI-PoI plane according to each experiment and C2 Approach.

Instead, a statistical test on the areas of the spreading was conducted. The effect of *C2 Approach* on the area of the CiCs in the DoI-PoI plane was modeled by a linear mixed model with a random *Experiment* effect. There was no effect for *C2 Approach* on the calculated areas [$F(4,11) = 0.81$, $p = .54$].

Table 1 shows the calculated areas covered by the CiCs for each C2 Approach and experiment.

Table 1: Average area covered by the CiCs.

C2 Approach	ELICIT-IDA	ELICIT-TRUST	abELICIT	IMAGE	WISE	PANOPEA	LS Means
Conflicted		0.002		0.018			-0.012
De-Conflicted	0.008	0.004		0.009	0.001	0.031	0.007
Coordinated	0.013	0.003	0.000	0.142			0.037
Collaborative	0.013	0.008	0.007	0.221	0.009	0.006	0.044
Edge	0.001	0.000	0.001			0.036	0.020

Even if the degraded conditions caused smaller deviations for some C2 Approaches, the differences are small, inconsistent, and not statistically significant. We would have expected Edge to have the smaller deviation, followed by collaborative and so on. Thus Hypothesis 1.2 is refuted. This implies that the gain in agility provided by more network-enabled C2 Approaches is caused by another factor. An alternative explanation is the ability of more network-enabled C2 Approaches to remain, in the average, in the correct region (globally, not relatively to their ideal location) of the C2 Approach Space. This hypothesis is tested in the next section.

4.3 H1.2: Absolute Position in the C2 Approach Space

A second question to explain the agility of more network-enabled C2 Approaches is: "Are more network-enabled C2 Approaches located in distinct regions of the C2 Approach Space that are favorable in terms of agility?" Figure 5 shows the position of each run in the C2 Approach Space for all experiments. Here again, computing the mean values corresponding to the location of each CiC (see Figure 5) for each C2 Approach would be simple but wrong because the points used to compute the average are randomly distributed and randomness in the selection of those independent variables may explain the observed results.

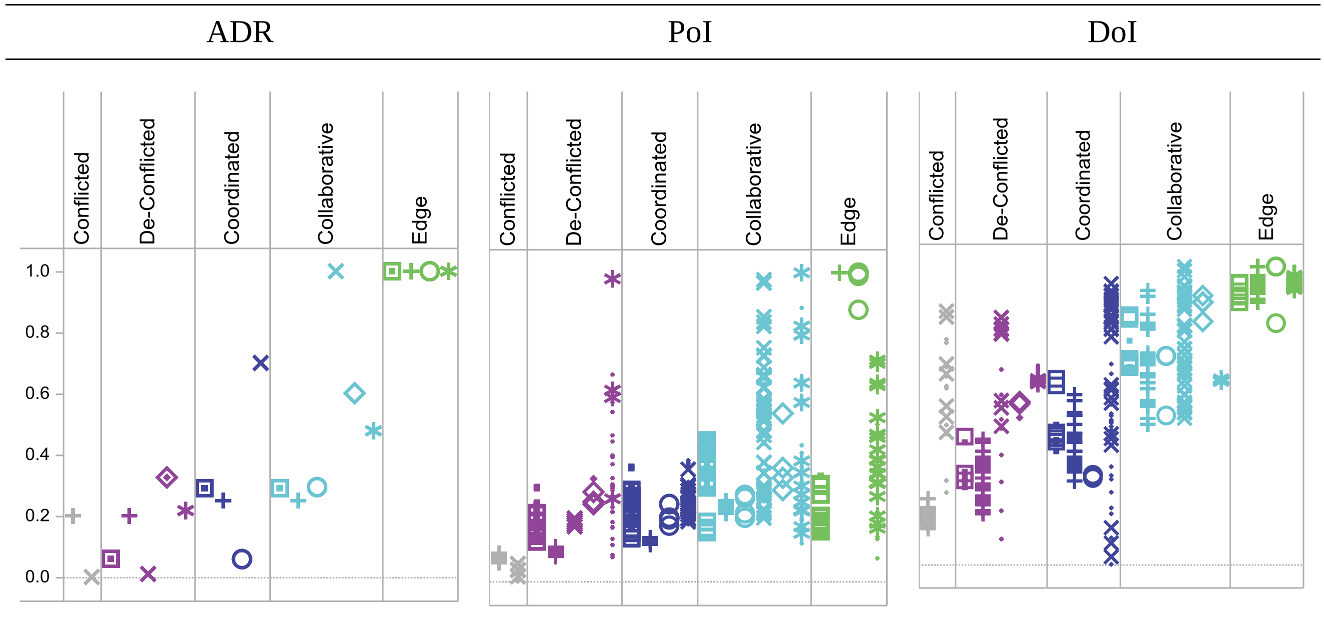

Figure 5: Mapping of all CiCs into each axis of the C2 Approach Space.

Instead, a mixed between-within experiment analysis of variance was conducted to assess the potential of the C2 Approach Space to determine if the location of each C2 Approach is statistically distinguishable. If it could be shown that the C2 Approaches occupy different regions of the C2 Approach Space and that more network-enabled C2 Approach are located in “higher” locations of the C2 Approach Space, then this would validate the predicate of this hypothesis. The relationship between *C2 Approach* and the position in the C2 Approach Space was modeled by a linear mixed model with a random *Experiment* effect in order to control for the unique aspects of each experiment. A Bonferroni correction (0.05/3) was applied to correct for type I error due to multiple tests. Table 2 presents the resulting least mean squares for each dimension and C2 Approach.

Table 2: Average ADR, PoI, and DoI values of all CiCs tested under each C2 Approach – estimated marginal means (standard error).

C2 Approach	ADR	PoI	DoI
Conflicted	-0.05 (0.13)	0.04 (0.07)	0.36 (0.12)
De-Conflicted	0.10 (0.12)	0.25 (0.06)	0.41 (0.11)
Coordinated	0.41 (0.12)	0.28 (0.06)	0.43 (0.11)
Collaborative	0.50 (0.12)	0.43 (0.06)	0.63 (0.11)
Edge	1.08 (0.12)	0.44 (0.06)	0.98 (0.12)

There was a significant effect for *C2 Approach* on the position for each of the dimensions of the C2 Approach Space, i.e. for ADR [$F(4,829) = 1284.00$, $p < .001$, $\eta 2 = .53$], PoI [$F(4,829) = 101.1$, $p < .001$, $\eta 2 = .12$], and DoI [$F(4,420) = 179.79$, $p < .001$, $\eta 2 = .42$]. Post hoc comparisons performed with Tukey’s test reveal that all pairs of comparisons for all dimensions are significant except for three pairs in DoI (Conflicted vs. Coordinated, Conflicted vs. De-Conflicted, and De-Conflicted vs. Coordinated) and two pairs in PoI (De-Conflicted vs. Coordinated and Collaborative vs. Edge). It follows from these results that although 1) circumscribing each C2 Approach depends on how we measure them, 2) the unique aspects of the experiment influence the observed values, and 3) C2 Approaches overlap in terms of DoI and PoI, the differences in locations in the C2 Approach Space are statistically significant and therefore we can accept the hypothesis that each of the N2C2M2 C2 Approaches is located in a distinct region of the C2 Approach Space. A an extension of this is that the C2 Approaches continue to be located in distinct regions of the C2 Approach Space in spite of adverse events or degraded conditions. In addition, and more importantly, Table 2 shows that Edge and Collaborative are able to retain significant higher values of ADR, PoI, and DoI simultaneously across all three dimensions when compared to Coordinated, De-Conflicted and Conflicted.

Figure 6 shows the average locations in the DoI-ADR and the DoI-PoI planes. The positions correspond to LS-mean with the consequence that they can be outside the 0-1 range because of the extrapolation used for missing values. Error bars indicate 0.95 confidence intervals. Confidence regions were not computed but correspond to ellipses (or ellipsoids for the three dimensions).

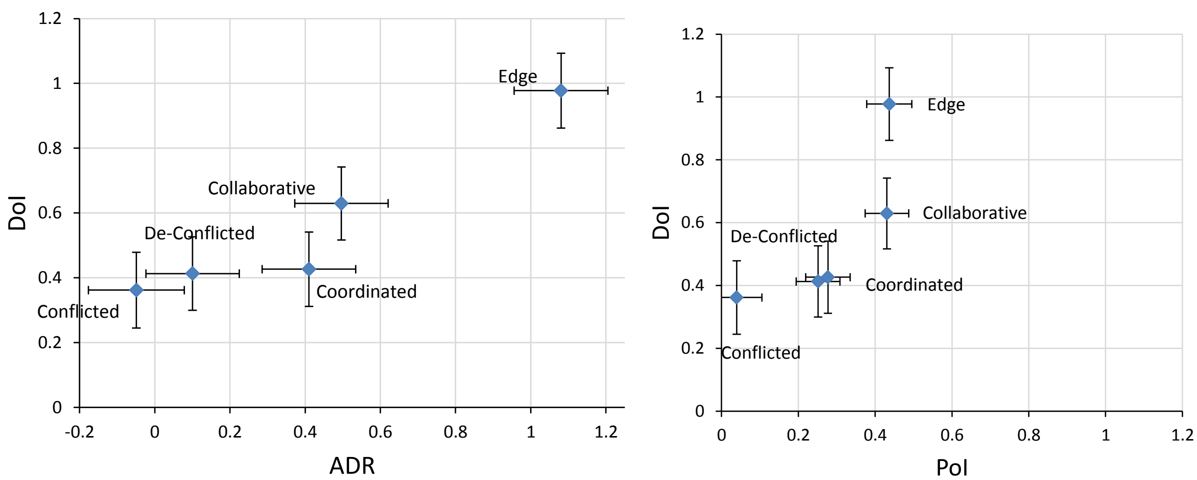

Figure 6: Average location of the C2 Approaches in the DoI-PoI and DoI-ADR planes.

Figure 7 maps each C2 Approach into a three-dimensional space (right) with colors and orientation similar to the theoretical model (left). Each ellipsoid is centered on the LS-mean of each C2 Approach and its radius corresponds to the 0.95 confidence interval in each dimension. The experimental data comply largely with the N2C2M2 theoretical model, however, it should be noted that the locations of the C2 Approaches in the C2 Approach Space were roughly estimated by the SAS-065 NATO group and such estimations were never intended as a strict definition as to the location of each C2 Approach. The region or spread of each C2 Approach is smaller for the experimental model than theoretical one, for the calculated regions represent confidence intervals and such intervals assume a normal distribution, which may not be entirely true in the real world. PoI is the dimension that departs the most from the theoretical model. It was also the most difficult measure to establish during the experimental design.

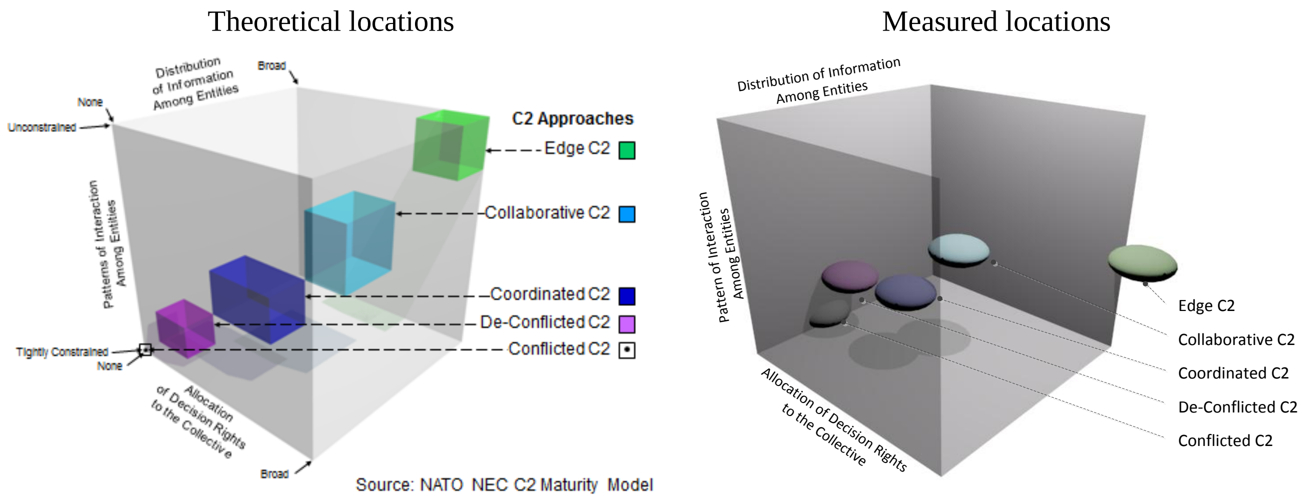

Figure 7: Average location of each C2 Approach in the C2 Approach Space.

One further observation is that the entire volume of the C2 Approach Space (see Figure 3) is not occupied. The reason for this is that locations tend to follow a pattern that corresponds to a distribution along the diagonal. There is a better way (or at least more compact way) to orientate the dimensions of the C2 Approach Space such that the first dimension of this new space captures most of the variability (i.e., the first axis of this space is aligned with the greater spreading of points), the second dimension captures the second higher amount of variability, and so on. For this purpose, a principal component analysis was conducted on the location in the C2 Approach Space for every CiC in order to identify the optimal transformation (rotation) and the amount of variance accounted for by each new dimension. Analysis indicates that the new referential is oriented according to the vector (0.589, 0.585, 0.558). The first dimension of the new referential accounts for 72.5% of the variability, the second dimension for 16.5%, and the third one for 12%. These results indicate that a C2 Approach "plane" would be sufficient to represent 88% of the C2 Approach Space. The results are similar when performed with the average location of each C2 Approach (vs. the individual CiCs) for each experiment. The first dimension accounts for 81% of the variability, the second for 12%, and the last one for 8%.

In summary, the results show that the N2C2M2 C2 Approaches are located in a distinct region of the C2 Approach Space and are robust in the face of adverse events or degraded conditions. The experimental model of the C2 Approach Space largely validates the N2C2M2 theoretical model, although there are some notable deviations.

4.4 H2: Correlation Between C2 Approach Space and Agility

The final hypothesis, that more network-enabled Approaches are manifest more agility, was tested and found to be supported by the evidence. Figure 8 shows the average position of each C2 Approach in each dimension of the C2 Approach Space (estimated marginal means calculated from all experiments, hence the explanation of negative values). The correlations are unambiguous, but looking at the individual correlation of each C2 Approach may be misleading because the dimensions of the C2 Approach space might be correlated among themselves.

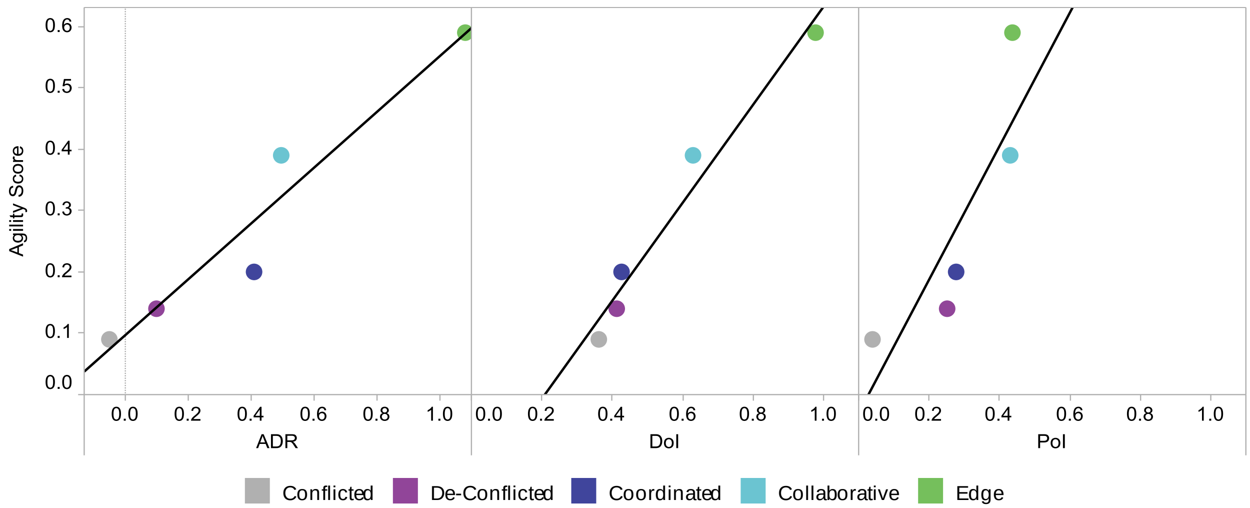

Figure 8: C2 Approach Agility and average position in the C2 Approach Space by C2 Approaches.

A more appropriate statistical Approach involves conducting a multiple regression analysis based on the three predictors (ADR, PoI, DoI) in order to see if the average position in the C2 Approach Space significantly predicted (and was correlated with) *Agility score*. The regression was calculated with 21 entries (number of C2 Approaches implemented by all experiments). The result of the regression indicates that the three predictors explain 51% of the variance (Adjusted $R^2 = 0.51$, $F(3,18) = 8.37$, $p = .001$). In summary, ADR, PoI, and DoIexplain about half the agility corresponding to each C2 Approach, confirming the potential of the C2 Approach Space to capture the conditions leading to agility. Table 3 summarizes the β, t-test and significance level for each predictor.

Table 3: Results of the multiple regression analysis with ADR, PoI, and DoI as predictors of agility score..

Dimension (Predictor)	β	t(14)	P*
ADR	0.460	2.75	0.01
PoI	-0.269	1.26	0.22
DoI	0.274	1.26	0.22

*note: $p < 0.25$ which is considered as valid in multiple regression analysis

The regression equation, described in Eq. 1, can predict which regions of the C2 Approach Space are associated with higher levels of agility, at the condition that the variables remain within the values used for constructing such model. Consequently, one must be cautious of not using extreme combinations of value for the variables, the consequence being incorrect prediction of agility. In addition, a regression does not guarantee that those predictors are the cause of agility, except for ADR which was independently controlled during the design of the experiment.

$$Agility\ Score = 0.0304 + 0.460\ ADR - 0.269\ PoI + .274\ DoI \qquad \text{Eq. 1}$$

ADR is the strongest predictor of agility. DoI is also positively but less correlated with agility. Finally, PoI negatively influences (is negatively associated with) agility. This finding contradicts the strong positive correlation observed in Figure 12 and what is proposed by theory. There are many reasons for this. First, DoI and PoI are correlated ($R^2 = 0.49$) and Figure 12 does not allow for the extraction of the individual contribution of DoI and ADR from PoI. Multiple regression analyses evaluate the individual effects of each variable while keeping other predictors constant. When other predictors are kept constant, PoI has a small negative impact. A second and perhaps more important reason is that the measures of PoI used for this analysis represent the frequency of interaction, not their quality. Finally, PoI seems to decrease to accommodate degraded conditions. For instance, when the network infrastructure is partially down, organizations increase the initiative to exchange information through other means of communication. Consequently, PoI is probably not a direct cause of agility but instead it enables DoI and one needs only so much interaction beyond which point the interactions can create unnecessary delays and workload. The exact relationship is certainly more complex and future research should consider selecting metrics of PoI that capture the quality of interactions and see if the same result is observed.

In another paper reporting on the same meta-analysis, an analysis measuring the impact of adopting a particular C2 Approach on agility (as measured by *Agility Score)* revealed that agility increases according to a quadratic equation when moving toward more network-enabled C2 Approaches. A possible explanation for this quadratic effect was the existence of a mediator variable[3] that behaves also in a quadratic manner. The position in the C2 Approach Space was then identified as the most likely mediator. In order to verify this hypothesis, a quadratic regression was conducted to see if it better predicts agility score. The result of the regression indicates that DoI, PoI, and ADR explain 71% of the variance of Agility Score (Adjusted $R^2 = 0.71$, $F(6,16) = 20.82$). This value is higher than the 51% obtained for the linear regression. The higher degrees of freedom of the fitted curve (7 instead of 4), especially in a context where there is 21 points to fit, contributes to improve this coefficient. But if the relation were close to linear, the difference would not be that large.

5 Conclusion

Organizations must be capable of operating in degraded environments that may arise from malfunctions, various circumstances or malevolent acts. The choice of the C2 Approach is an important, perhaps critical consideration when dealing with such environments. In a previous effort, the NATO group SAS-065 defined a number of C2 Approaches that correspond to various ways to accomplish C2 functions. These Approaches differ on at least three major aspects of an Approach to C2: the allocation of decision rights (ADR), the pattern of interaction among entities (PoI), and, distribution of information among entities (DoI), in a collective endeavor. More recently, the NATO Research Group SAS-085 conducted a meta-analysis of a series of simulation-based experiments to study the effect of adopting a specific C2 Approach on agility and performance. An additional objective was to understand the impact of the position in the C2 Approach Space in presence of change in circumstances (CiCs) for which degraded environments represent an important portion. The current paper reports some hypotheses tested for that purpose and their results.

[3] A mediator variable is a third explanatory variable (e.g., location in the C2 Approach Space) that explains the mechanism that underlies an observed relationship between an independent (e.g., *C2 Approach*) and a dependent variable (e.g., *Agility Score*).

H1.1 tested if more network-enabled C2 Approaches are better able to maintain their relative position in the C2 Approach Space when compared to the location of the baseline/non-degraded condition. The results do not support this hypothesis. Even if some C2 Approaches were less affected than others by adverse conditions, the differences are small and inconsistent..

H1.2 tested if more network-enabled C2 Approaches are located in distinct regions of the C2 Approach Space and if they are favorable in terms of agility. The results strongly support this hypothesis. In addition, calculated positions are really close to those proposed by SAS-065 theory. The main exception is for the PoI dimension for organizations operating in Edge.

Finally, H3 tested if the dimensions of the C2 Approach Space is positively correlated (or predict) with the measure of agility. Both a linear and a quadratic multiple regression analysis were conducted with DoI, PoI, and ADR as predictor of the measure of agility (*Agility Score*). The linear regression indicated that the three predictors explain 51% of the variance of the measure of agility. DoI and ADR are positively correlated with the measure of agility while PoI is negatively correlated. This negative correlation is explained by the choice of metrics to represent PoI; they capture the quantitative nature of the interactions, not their efficiency or qualitative aspect. In addition, current results show that PoI is probably not the cause of agility but instead a consequence of it to accommodate degraded conditions. The exact relationship is certainly more complex though. Future research should consider selecting metrics of PoI that capture the quality of interactions. As for the quadratic regression, it explains 71% of the variance of the measure of agility. The quadratic relationship supports another quadratic relationship found by Bernier et al. (2013). In summary, the location in the C2 Approach Space explains between half and three-quarter of the agility corresponding to each C2 Approach, confirming the potential of the C2 Approach Space to capture the conditions leading to agility. Being able to operate in some of these regions should be a priority for military organizations because it creates conditions that would make them better able to successfully cope with denied and degraded environments.

Acknowledgements

The authors gratefully acknowledge the inputs from Alberto Tremori, Agostino Bruzzone, and Marco Manso for their very valuable contributions to this experiment with simulation data and comments.

References

Alberts, D. S., Bernier, F., Chan, K., & Manso, M. (2013). C2 Approaches: Looking for the "Sweet Spot". In *Proceedings of the 18th ICCRTS*. Alexandria, VA, USA.

Alberts, D. S., Huber, R. K., & Moffat, J. (2010). *NATO NEC C2 maturity model*. United-States: DoD Command and Control Research Program.

Andrew, A. M. (1979). Another Efficient Algorithm for Convex Hulls in Two Dimensions. *Info Proceedings Letters*, *9*, 216–219.

Bernier, F., Alberts, D. S., & Manso, M. (2013). International Multi-Experimentation Analysis on C2 Agility. In *Proceedings of the 18th ICCRTS*. Alexandria, VA, USA.

Bernier, F., Alberts, D. S., Pearce, P., Manso, M., & Chan, K. (2013). Meta-Analysis of Multiple Simulation-Based Experiments. In *Proceedings of the 18th ICCRTS*. Alexandria, VA, USA.

Bruzzone, A. G., Tremori, A., & Merkuryev, Y. (2011). Asymmetric Marine Warfare: PANOPEA a Piracy Simulator for Investigating New C2 Solutions. In *Proceeding of the SCM MEMTS Conference* (p. 32). Saint-Petersburg, Russia.

Chan, K., Cho, J. H., & Adali, S. (2012). Composite Trust Model for an Information Sharing Scenario. In *Proceedings of the Ubiquitous Intelligence & Computing and 9th International Conference on Autonomic & Trusted Computing (UIC/ATC)* (pp. 439–446). Fukuoka, Japan.

Lizotte, M., Bernier, F., Mokhtari, M., & Boivin, E. (2013). *IMAGE Final Report: An Interactive Computer-aided Cognition Capability for C4ISR Complexity Discovery* (No. TR 2013-397). Québec, Canada: Defence R&D Canada - Valcartier.

Manso, M., & Nunes, P. (2008). ELICIT and the Future C2: Theoretical Foundations for the Analysis of ELICIT Experiments. In *Proceedings of the 13th ICCRTS* (pp. 17–19). Seattle,WA, USA.

Pearce, P., Robinson, A., & Wright, S. (2003). The Wargame Infrastructure and Simulation Environment (Wise). In *Proceedings of the Knowledge-Based Intelligent Information and Engineering Systems Conference* (pp. 714–722). Oxford, UK.

Rickards, D. A. (2010). *NO AIR: Cyber Dependency and the Doctrine Gap*.

Ruddy, M. (2007). ELICIT–The Experimental Laboratory for Investigating Collaboration, Information-sharing and Trust. In *Proceedings of the 12th International Command and Control Research and Technology Symposium* (pp. 19–21). Retrieved from http://www.dodccrp.org/events/12th_ICCRTS/CD/html/papers/155.pdf

Steinberg, D. M., & Bursztyn, D. (1998). Noise factors, dispersion effects, and robust design. *Statistica Sinica*, *8*, 67–86.

US Navy. (2012). *Command and Control in a Denied or Degraded Environment (C2D2E)* (Tactical Memo). Norfolk, VA, USA. Retrieved from http://www.navy.mil/submit/display.asp?story_id=67733

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YY)	2. REPORT TYPE	3. DATES COVERED (From – To)
October 2013	Final	

4. TITLE AND SUBTITLE
Coping with Degraded or Denied Environments in the C2 Approach Space

5a. CONTRACT NO. DASW01 04 C 0003

5b. GRANT NO.

5c. PROGRAM ELEMENT NO(S).

6. AUTHOR(S)
François Bernier, Ph.D., Defense R&D Canada—Valcartier; Kevin Chan, Ph.D., U.S. Army Research Laboratory; David S. Alberts, Paul Pearce, Ph. D., Defence Science and Technology Laboratory

5d. PROJECT NO.

5e. TASK NO. AA-6-3630

5f. WORK UNIT NO.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311-1882

8. PERFORMING ORGANIZATION REPORT NO.
IDA NS Document D-5040

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311-1882

10. SPONSOR'S / MONITOR'S ACRONYM(S)
IDA

11. SPONSOR'S / MONITOR'S REPORT NO(S).

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NATO Network Enabled Operations (NEC) C2 Maturity Model (N2C2M2) defines a number of command and control (C2) Approaches that correspond to various ways to accomplish C2 functions. These Approaches are defined by organizational the allocation of decision rights, patterns of interaction, and the distribution of information. Recent work in C2 theory has considered the differences in performance relative to the C2 Approach that is adopted. This work has investigated the idea that an optimal operating region of the C2 Approach Space can be identified for particular missions and circumstances, where optimal is a function of effectiveness, efficiency and agility. While circumstances that are characterized by the presence of degraded network conditions or hostile or extreme environments is of great interest, the performance of various c2 Approach options under these conditions have not been well studied. This paper focuses on the relative resilience of organizations as a function of their C2 Approach (a key component of agility). We explore the relationship between C2 Approach and performance under degraded information and communications environments using a set of six unique simulation experiments.

15. SUBJECT TERMS
C2, Command and Control, Agility, NATO, C2 Maturity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NO. OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include Area Code)
U	U	U	UU	22	