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Graph Theoretical Analysis of Network Centric Operations Using Multi-Layer Models

Ann Wong-Jiru

GRAPH THEORETICAL ANALYSIS OF NETWORK CENTRIC OPERATIONS USING MULTI-LAYER MODELS

THESIS

Ann Wong-Jiru, Major, USAF

AFIT/GSE/ENY/06-S01

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GSE/ENY/06-S01

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Ann Wong-Jiru, BS, MS

Major, USAF

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Ann Wong-Jiru, BS, MS
Major, USAF

Approved:

John M. Colombi, Lt Col, USAF (Chairman)	5 Sep 06 date
Laura R.C. Suzuki, Maj, USAF (Member)	5 Sep 06 date
Dr. Robert F. Mills (Member)	5 Sep 06 date

AFIT/GSE/ENY/06-S01

Abstract

As the Department of Defense continues its transformations to a network centric force, evaluating DoD's progression towards net-centricity remains a challenge. This research proposes to extend the Network Centric Operation Common Framework Version 2.0 (draft) with the metrics based in graph theory and, specifically addresses, among other metrics, the measurement of a net-centric force's mission effectiveness. The research incorporates the importance of understanding network topology for evaluating an environment for net-centricity and using network characteristics to help commanders assess the effects of network changes on mission effectiveness.

The multi-layered model of Network Centric Operations and interlayer mapping are introduced to address the interdependent contributions of people, systems, and processes to the success of net-centric operations. A layered network model was populated with data derived from the 2006 Joint Expeditionary Forces Experiment (JEFX). Both static and dynamic network analyses were performed to characterize the network structures and to demonstrate how the interlayer mapping allows networks changes at one layer affects the networks characteristics of other layers. Thirty four excursions were performed on a three-layer model of JEFX network centric operations and the network characteristics were measured using twelve graph-theoretical metrics. The analysis is able to reveal the average percent reduction in network effectiveness as compared to the baseline model.

To Mom and Dad, for your love and giving me the foundation to grow and achieve.
To my sisters, you are my "Mei-mei" and "Peng-you" always.

To my husband, for supporting my dreams! Wo ai ni!

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Relevant JEFX Acronyms

ADSI:	Air Defense System Integrator
CAOC:	Combined Air Operations Center
CoT:	Cursor On Target
DTC:	Dynamic Targeting Cell
IOTA:	Infrastructure Operations Tools Access
ISR:	Intelligence, Surveillance, Reconnaissance
SIDO:	Senior Information Duty Officer
TDO:	Tactical Duty Officer
TTNT:	Tactical Targeting Network Technology
WEEMC:	Web-Enabled Execution Management Capability

GRAPH THEORETICAL ANALYSIS OF NETWORK CENTRIC OPERATIONS USING MULTI-LAYER MODELS

I. Introduction

1.1 Background

As the Department of Defense continues its transformations to a network centric force, evaluating DoD's progression towards net-centricity remains a challenge. At the Electronic Systems Center, Hanscom AFB, there are ongoing efforts to contribute to this field. These efforts cover a broad spectrum of study, from investigating applications of complexity theory to research on how to make systems more net-centric, such as on-going work on Military Satellite Communication systems (MILSATCOM).

Through the sponsorship of the Global Information Systems Group at Hanscom AFB, this thesis aimed to leverage the fairly recent concepts of Network Centric Warfare (NCW) and Operations (NCO) and the NCO Common Framework, together with network theory and graph theory, to produce a model and methodology for evaluating net-centricity, as well as prove the concept through analysis.

1.2 Problem Statement

1.2.1 Review of the Network Centric Operations Common Framework

As the Department of Defense continues its transformations to a network centric force, measuring the DoD progression towards net-centricity remains a challenge. The establishment of the Network Centric Operation Common Framework (NCO-CF), currently at Version 2.0 (draft), proposes attributes and metrics with which to evaluate environments' net-centricity levels. While the NCO-CF does quantify complex, net-centric factors, the subjective nature of several metrics do not necessarily allow for repeatable, analytical results. Repeatable analysis is important to a wide array of activities, such as conducting experimentation, evaluating the merits of process improvements, and development of new technologies. For the DoD to measure its net-centric progress with fidelity, further objective measures should be introduced into the NCO-CF. These measures should not only be node-oriented, but take into account the network topology and the contributions of all the nodes and connections between them to the overall network. Objective measures results in a qualitative way to characterize those networks, and a baseline network can be established. These baselines can then be used for conducting experiments or evaluating system designs.

1.2.2 The Cause and Effect Challenge: What the Commander Wants to Know

Understanding how the structure of a network effects operations may help a commander evaluate performance and determine possible courses of action. One of the major challenges of evaluating the effectiveness of command and control (C2) has been to connecting a cause to a specific mission-related effect. The commander also wants to know how a change, whether it is tangible or intangible, will affect his mission effectiveness. For instance, when a piece of communications equipment fails in the C2 system, there should be a method to determine who is affected and what tasks will be disrupted, so alternatives can be used. Furthermore, a commander wants to be able to determine which mission objectives are impacted by the equipment failure. They may also want to know how a process improvement or a modification to a system may enhance mission effectiveness. Having this knowledge will allow the commander to make better decisions to ultimately meet the mission objective.

A specific example can be used to illustrate this "cause and effect challenge." The source, a Senior Duty Officer at the Air Force Network Operations and Security Center, describes a situation where being able to connect a cause, a faulty communications circuit, to a mission impact resulted in a faster fix. The faster fix allowed the unit to resume their mission with minimal delay.

> A Defense Information Service Agency (DISA) circuit was causing significant problems…but all any of the bases could do was tell me the amount of packet loss they were experiencing. Packet loss means something to communicators, but nothing to operators and didn't peak too much interest in DISA [to fix it] either…However, [in this case bases identified mission impacts…A command] was unable to upload any medical or financial information for [personnel] getting ready to deploy...file transfers were timing out due to packet loss. Now I have a mission impact, because I can't deploy people to the fight. This impact assessment got DISA to expedite their service request from 2 weeks to within 48 hours (Stanley, 2005:103-4).

1.3 Research Objectives

The objectives of this research are the following:

-- Extend the NCO-CF using metrics based in graph theory and, specifically addresses, among other metrics, the measurement of a net-centric force's mission effectiveness.

-- Illustrate the importance of quantifying the baselining characteristics of a network's topology in the course of evaluating networks for net-centricity.

-- Introduce a multi-layer model for NCO that allows analysis of mission effectiveness by inter-relating the cause and effect of all networks that contribute to NCO.

-- Analyze networks, derived from Joint Expeditionary Forces Experiment (JEFX) data, both statically and dynamically to show how network metric change with changes in network topology and the related NCO implications.

1.4 Methodology

First, NCO-CF was reviewed to identify areas which could be extended with additional metrics. The review targeted NCO-CF areas where the metrics were subjective, and also where additional metrics could offer more insight into the existing the NCO-CF metric. Then, metrics based on the study of graph theory were reviewed and nominated for use in extending the NCO-CF.

The next step was to find a more cohesive model of the networks that support NCO. Using the concept of mapping layers of graphs, the multi-layer model of NCO was developed. To remain consistent with the scope of the NCO-CF, this approach models the net-centric contributions of people, systems, and processes as inter-related networks, but allows each network to also be investigated independently. Each network in the model is depicted as a simple graph (defined as a set of vertices, a set of edges, and their associations with no self loops). The model of net-centric operations used in the research was derived from data from the JEFX held in 2006.

Using the multi-layer model and the graph theoretical metrics, both static and dynamic network analysis was performed. The static analysis determined the characteristics of each network, baselining the networks characteristics based on the network's structure, or topology. Dynamic analysis followed. The edges of a network were iteratively removed and the effects of those removals on overall mission effectiveness and contributing networks were assessed.

1.5 Scope, Assumptions, and Limitations

The networks modeled are derived from available DoD Architectural Framework (DoDAF) and other documentation from JEFX 2006. To further scope the number of considerations, only three of the over 50 possible operational mission threads were chosen for inclusion in the analysis. The network elements in the model were those that were documented to support those three operational threads.

JEFX was chosen originally for the possibility of using live-fly data to verify the analysis. However, the extensiveness of the necessary data collection was prohibitive, but could be pursued for future JEFX events.

All nodal relationships incorporated any instances of self-looping into the parent node. The objective was to treat all networks as simple graphs.

1.6 Preview

Though the multi-layer model of NCO specifies five layers, three were used specifically for the research: an Application-System layer, a People layer, and a Process layer. Each layer represents a major contributor to successful net-centric operations. The Application-System layer represents the technology supporting NCO. This is the lowest layer. The People layer represents the working relationships and human element of NCO. The People layer is placed above the Application-System layer since applications and systems are used by operators. The top-most layer in this analysis is the Process layer, which embodies any activity. For this research, the processes under review are the three JEFX operational threads: Enhancing command and control situational awareness (C2 SA), Prosecuting Time Sensitive Targets (Pros TST), and Executing Non-traditional Intelligence, Reconnaissance, and Surveillance (NTISR). The Process layer is the top-most layer of the model because all other layers exist to support and complete a process. The Process layer is used to assess mission effectiveness--when a process is not completed, mission effectiveness is degraded. The inter-relationships between the layers are connected by mapping each network on the other. Then, if one network experiences a change, the effects of that change can be rippled through the rest of the networks.

The use of graph theoretical metrics proved insightful and useful in obtaining characteristics of the JEFX networks through static analysis. The advantage of metrics with a graph theory pedigree is that the results are dependant on the topology of the network and tend to be very specific to that network. The applicability of these metrics to NCW is discussed.

The multi-layer model was very effective in showing the effects of dynamic changes to the networks. When the Application-System layer was altered, the network effects could be observed and measured at the People and Process layers. The commander may be interested in the changes in each layer for different reason, but of particular interest is how his mission effectiveness can be characterized at the Process layer.

II. Literature Search

2.1 Joint Vision 2020

U.S. Department of Defense (DoD) is undergoing a transformation in how modern warfare is supported and conducted. In 2000, the DoD published Joint Vision 2020 (JV2020), calling for the military to evolve to a network centric force. JV2020 states “the primary purpose of [America’s Armed Forces] has been and will be to fight the Nation’s wars” (DoD, 2000:1). The purpose of military transformation is to create a force which can execute “Full Spectrum Dominance,” that is “the ability of US forces, operating unilaterally or in combination with multinational and interagency partners, to defeat any adversary and control any situation across the full range of military operations” (DoD, 2000:6). The elements of Full Spectrum Dominance are shown in Figure 1.

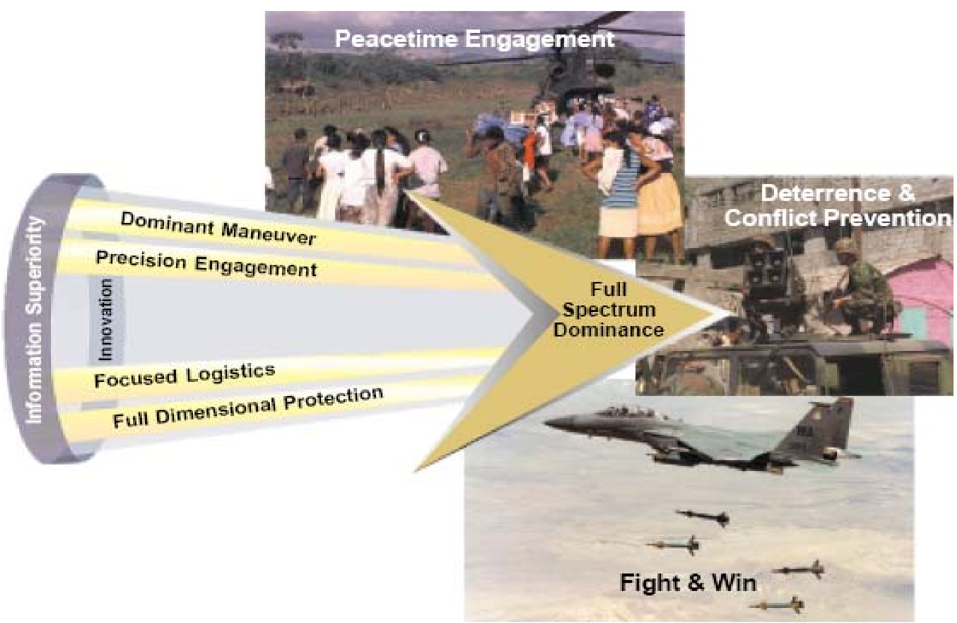


Figure 1: Elements and Effects of Full Spectrum Dominance, (JV2020, 2000:2).

Full Spectrum Dominance also relies upon Information Superiority as one of its primary foundations and contributing enablers. Joint Publication 1-02, DoD Dictionary of Military and Associated Terms, defines Information Superiority as "the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same" (DoD, 2006:259). While obtaining information for oneself and denying it to adversaries has merit, how that information is used to gain a competitive advantage and meet command objectives are the true goals. "Information Superiority provides the joint force a competitive advantage only when it is effectively translated into superior knowledge and decisions. The joint force must be able to take advantage of superior information converted to superior knowledge to achieve 'decision superiority'" (DoD, 2000:8).

The other piece of the foundation is Innovation. JV2020 defines Innovation "in its simplest form, is the combination of new 'things' with new 'ways' to carry out tasks" (DoD, 2000:10). Innovations are not limited to technological areas, but are intended to include changes in all areas of the Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities (DOTMLPF) spectrum. "Ultimately, the goal is to develop reasonable approaches with enough flexibility to recover from errors and unforeseen circumstances" (DoD, 2000:11). JV2020 points out the importance of encouraging professionals to be innovative and of providing experimentation venues to allow those innovations in the DoD to be tested. One such experimentation venue is the Joint Expeditionary Forces Experiment (JEFX).

JV2020 also recognizes the importance of Interoperability in reaching Full Spectrum Dominance. Again referring to Joint Publication 1-02, Interoperability is defined as “the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together” (DoD, 2006:274). As the definition shows, Interoperability, like Innovation, is not limited to technological interoperability, but extends to processes and people. Whether it’s systems that aren’t designed to understand each other’s data or two people who do not understand each other’s intent, both situations can lead to failure in meeting a commander’s intent. Though less tangible, cultural, organizational, and training interoperability are just as important as system interoperability.

2.2 Network Centric Warfare Theory Basics

The leading theory of warfare that incorporates JV2020 concepts of Information Superiority, Innovation, and Interoperability as it leads to Full Spectrum Dominance is Network Centric Warfare (NCW). In January 2005, the DoD Office of Transformation, under the Office of the Secretary of Defense, published “The Implementation of Network-Centric Warfare.” In answer to the question “What is NCW?” the Office writes, “[NCW] broadly describes the combination of strategies, emerging tactics, techniques, and procedures, and organizations that a fully or even a partially networked force can employ to create a decisive warfighting advantage” (OFT, 2005:3). More importantly, the Office states the four tenets of NCW:

1. A robustly networked force improves information sharing.
2. Information sharing enhances the quality of information and shared situational awareness.
3. Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command.
4. These, in turn, dramatically increase mission effectiveness (OFT, 2005:7).

In addition to these tenets, NCW governing principles have been defined. They are listed in Figure 2.

Governing Principles

- Fight first for ***information superiority***
- Access to information: ***shared awareness***
- ***Speed of command*** and decision making
- ***Self-synchronization***
- ***Dispersed forces***: non-contiguous operations
- ***Demassification***
- **Deep sensor reach**
- ***After initial conditions*** at higher rates of change
- ***Compressed operations*** and levels of war

Figure 2: NCW Governing Principles, (OFT, 2005:13).

In their book, Power to the Edge, David S. Alberts and Richard E. Hayes offer parallel thoughts to the NCW theory. They state that DoD transformation is an opportunity to take advantage of the Information Age and its advances. However, as the DoD incorporates and updates its technologies (modernization), Alberts and Hayes points out that there is a "road less traveled" that must also be transformed. This is the transformation that "must focus on [command and control], where information is translated to actionable knowledge" (Alberts and Hayes, 2003:4).

This transformation of command and control (C2) is coined "power to the edge." Alberts and Hayes explains,

> Power to the edge is about changing the way individuals, organizations and systems relate to one another and work…it involves the empowerment of individuals at the edge of the organization (where the organization interacts with its operating environment to have an impact or effect on that environment) in, in the case of systems, edge devices. Empowerment involves expanding access to information… [it] implies adoption of an edge organization, with greatly enhanced peer-to-peer interactions (Alberts and Hayes, 2003:5).

Instilling "power to the edge" is deemed essential to a successful application of NCW theory to current and future military operational success. If edge organizations are empowered with the resources to achieve "decision superiority," then information superiority will have successfully enabled Full Spectrum Dominance, as desired by JV2020. The evolving NCO-CF metrics are available to measure how well this transformation is taking place.

2.3 The Network Centric Operations - Common Framework (NCO-CF)

With the emerging theory of warfare and its established tenets, the DoD recognized that there needed to find a way to measure the degree and effectiveness of the NCW theory. In essence, there needed to be an established way to answer the question, "How well are we progressing towards NCW?" Potentially, this evidence could then be used to inform DoD investment decisions across the doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) functional areas (OFT, 2005:31). As a result, the Office published the Network Centric Operations Conceptual Framework (NCO-CF). Version 1.0 was released in November 2003 and a draft Version 2.0 was released in June 2004, with additional updates expected as the document matures.

Figure 3 depicts the Conceptual Framework as found in NCO-CF Version 2.0. The framework encompasses the four NCW tenets and categorizes the key tenet concepts into four domains:

1. Physical: where effects take place and where other supporting infrastructure and information systems exist
2. Information: where information is created, manipulated and shared
3. Cognitive: where perceptions, awareness, beliefs, and values reside and where, as a result of sensemaking, decisions are made,

4. Social: set of interactions between and among force entities (Garska and Alberts, 2004:56).

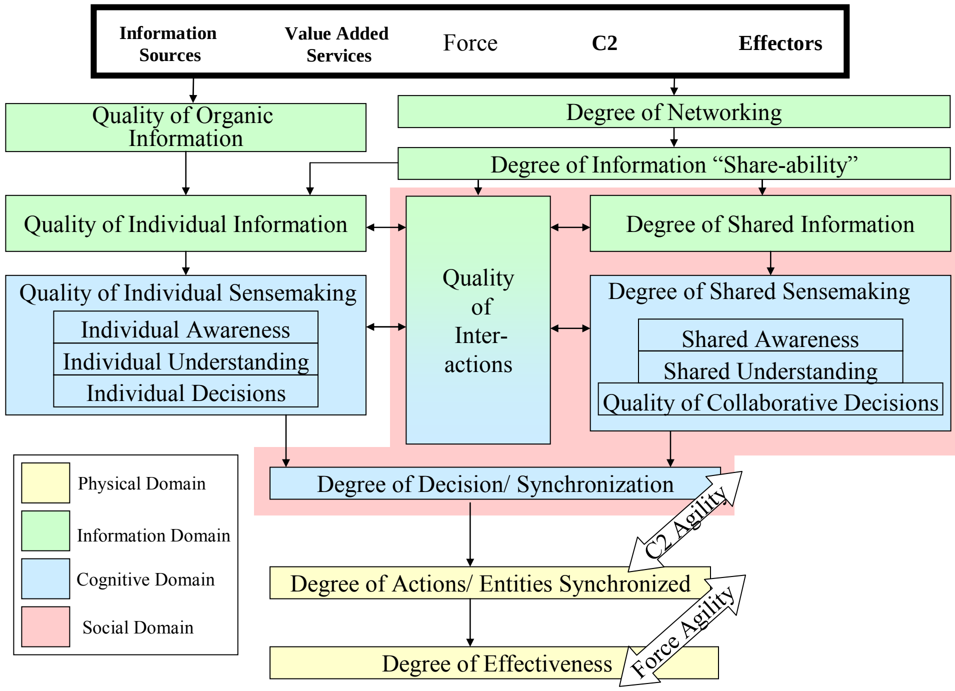


Figure 3: NCO Conceptual Framework, (Garska and Alberts, 2004:4).

The CF incorporates the DOTMLPF spectrum using these four domains. Each major category has sub-elements called attributes. The NCO-CF provides both definitions for each attribute as well as a suggested metric for measuring that attribute.

2.4 Applying Complexity Theory Concepts to NCW

The entities (people, processes, technology) that enable NCW, when combined to form a whole, can be characterized as a complex system. The four tenets of NCW convey the desired macroscopic behaviors of NCW.

In his book, "Complexity Theory and Network Centric Warfare", James Moffat provides a list of complexity theory concepts and translates them into an information-based, NCW frame of reference. Table 1 is a summary of those concepts.

Table 1: Complexity and the Information Age Force, (Moffat, 2003:49).

Complexity Concept	Information Age Force
Nonlinear interaction	Combat forces composed of large number of nonlinearly interacting parts.
Decentralized control	There is no master "oracle" dictating the action of each and every combatant.
Self-Organization	Local action, which often appears "chaotic," induces long-range order.
Nonequilibrium Order	Military conflicts, by their nature, proceed far from equilibrium. Correlation of local effects is key.
Adaptation	Combat forces must continually adapt and coevolve in a changing environment.
Collectivist Dynamics	There is a continual feedback between the behaviour of combatants and the command structure.

He further extends this translation to describe how the NCW force entities interacting with each other and the information provided culminate in emergent behaviors, that is, how the microscopic behaviors of force entities contribute to macroscopic behaviors.

> We can describe such a system as *loosely coupled* to capture the local freedom available to the units to prosecute their mission within an awareness of the overall intent and constraints imposed by high-level command. This also emphasises the looser correlation and *nonsynchronous* relationship between inputs to the system…and outputs from the system... In this process, information is transformed into "shared awareness,"… This leads to units linking up with other units, which are either local in a physical sense or local…(self-synchronisation). This in turn leads to emergent behaviour in the battlespace… (Moffat, 2003:49).

Figure 4 depicts this statement in a graphical sense and captures the major areas stated in the four tenets of NCW, where "emergent behavior" could be a label for "increased mission effectiveness." In the area of measuring mission effectiveness, the NCO-CF proposes the concept of Degree of Effectiveness, with Achievement of Objectives, Agility, Time, and Efficiency as supporting attributes.

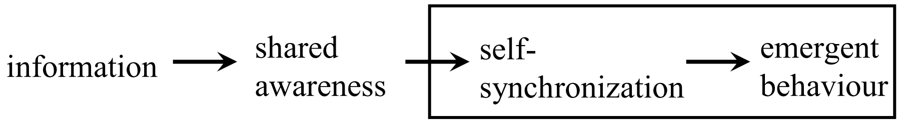


Figure 4: Information Leading to Emergent Behavior, (Moffat, 2003:50).

2.5 The Importance of Studying Network Structure and Dynamics

In his book, Six Degrees: the Science of a Connected Age, Duncan J. Watts poses a thought-provoking question: “How does individual behavior aggregate to collective behavior?” Watts, 2003:24). He gives an example of the human brain,

> A human brain…is in one sense a trillion neurons connected together in a big electrochemical hump, but…the brain is clearly much more, exhibiting properties like consciousness, memory, and personality, whose nature cannot be explained simply in terms of aggregations of neurons (Watts, 2003:24-25).

A collective of individuals that interact with each other produces emergent behavior. One can understand the microcosm of one neuron very well, and still not be able to predict how its interactions with its neighbors may affect the macrocosm. Furthermore, because each neuron’s microcosm may be different from its neighbor’s, the “domino effect” is too simplistic a model to use to predict macroscopic behavior. Such macrocosms exhibit complex behaviors.

The science of networks and network theory aims to answer Watts’ question. One area of this science is the study of the network structures. How a network is structured and its characteristics are fundamental to understanding what the network is potentially capable of. For example, the network structure, or topology, of the graph in Figure 5 is often known as star network.

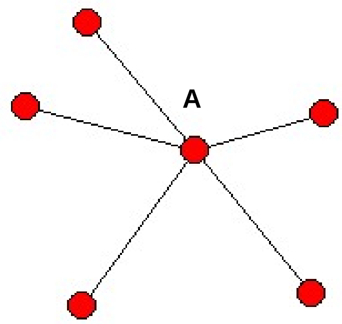


Figure 5: Graph of a Star Network

A characteristic of a star network is that the center node, labeled A, is a neighbor of all the other nodes, but the other nodes are not neighbors of each other. What does this characteristic reveal about the potential use of this network? It reveals that if this star network were to be used for data transfer, node A must be involved in every data transaction between the outer nodes. Depending on the objectives of the network designer, the network's topology may be changed, kept, or discarded. This type of network structure analysis is often considered static analysis because the characteristics of the network are not undergoing any changes over time. Any data that is gleaned is based upon the snap-shot of the network of interest.

Another area of network study is dynamic analysis. Dynamic network analysis studies the effects of a network when interactions between nodes are changed over time. In the example of the human brain, dynamic analysis may study the overall brain activity over time when certain neurons are stimulated. For a network of city dwellers, dynamic analysis may investigate the spread of a disease through the population. The outcome of the dynamic analysis is predicated upon the underlying structure of the network that is being acted upon, in addition to the rules and logic governing network elements. Furthermore, interpreting the results of dynamic analysis should take into account that underlying structure.

If the entities that enable NCW can be considered nodes in a network or a series of networks, then another facet to measuring network centricity is to understand the network structures, characteristics, and dynamics of those networks. In a connected age, therefore, *what happens and how it happens depend on the network* (Watts, 2003:28).

2.6 Previous NCW Analysis

Many methodologies have been used for evaluating various networks and network issues. Each is initiated from a different point of view and all result in valuable insights. The first is a brief summary of how the information technology (IT) community provides services management. Next, for NCW, the Joint Tactical Information Distribution System (JTIDS) Air-to-Air Operations Study produced an evaluation of networked blue forces. That study, which was the first to apply the NCO-CF, also evaluated the performance of the NCO-itself. The last related analysis was documented in "Methodology for Analyzing Complex Command and Control Networks." This effort applied complex system metrics to a military exercise to show how adaptive behavior could be measured, evaluated, and translated into real world improvement recommendations.

2.6.1 Information Technology Operational Impact Analysis

Several constructs have been developed to address how operational impact analysis may be performed. A survey of constructs that have proliferated in the IT community was completed by Capt Jeffrey Stanley as part of his Air Force Institute of Technology thesis entitled, "Enabling Network Centric Warfare Through Operational Impact Analysis Automation."

IT Governance generally describes management concepts of IT services. There are two main goals of IT management. The first is ensuring IT services add value to the business and the second is to ensure that IT risks are mitigated (Stanley, 2005:11). The IT Infrastructure Library (ITIL) and British Standard 15000 are IT Service Management frameworks, providing methodologies. The application of such constructs in an NCW environment would be very valuable in helping the commander understand the cause and effect of changes in his networks from an IT perspective. As an example of such application, a commander may be able to attribute a delay in processing a deployment line to a circuit failure and be able to justify priority maintenance on that circuit (Stanley, 2005:104). Such value-chain traceability is not status quo.

A commander leading a net-centric force is in charge of a dynamic set of interrelated elements. IT Governance is designed to account for relationships more commonly found in the IT community. While the IT element is vital to delivering Information Superiority, NCW, as stated previously, is broader than the information technology and the functions needed to sustain. For NCW, another different approach may be warranted.

2.6.2 JTIDS Air-to-Air Operations Study

Using the NCO-CF framework, the Office of Transformation conducted a series of case studies. A total of seven studies have been completed as of the release of NCO-CF Version 2.0 (Draft). The prototype study was of the "Air-to-Air Operations JTIDS Exercises", completed by RAND Corporation. This study had a two-fold purpose. First, the study was the first application of the metrics introduced by the NCO-CF on a case that exhibited NCW characteristics. Second, the study aimed to determine why networking via Link 16 improved the warfighting capabilities of the force.

The case study was based on available data and interviews from a mid-1990's evaluation. The two main scenarios of the case study consisted of blue aircraft, F-15s and Airborne Warning and Control System (AWACS), engaging with red adversary aircraft. In one scenario, the blue aircraft conducted a series of engagements using voice-only communications. In a second scenario, the blue aircraft engaged using both voice and Link-16 data links. The data showed, for engagements where the blue aircraft were both voice and data-linked, the kill ratio was two and a half times higher than the voice-only scenarios. The case study applied the NCO-CF metrics to the engagement data to find out if this improvement was due to increased net-centricity.

Upon applying the metrics, RAND found, while the blue forces started out with the same information about the situation, the addition of the data link contributed to the increased kill ratio because the data link contributed to higher metrics in such areas as Degree of Shared Information and Degree of Shared Sensemaking. Figure 6 shows the scoring of both the voice only and voice- and data-linked engagement scenarios.

Since this study was the prototype use of the NCO-CF metrics themselves, RAND also provided an evaluation of the metrics and their use. Overall, RAND concluded that, in general, for the metrics they were able to use, there were no major deficiencies in the metric's design. (Since the data was archival and collected before the introduction of the NCO-CF, RAND did not have all the data to use each metric).

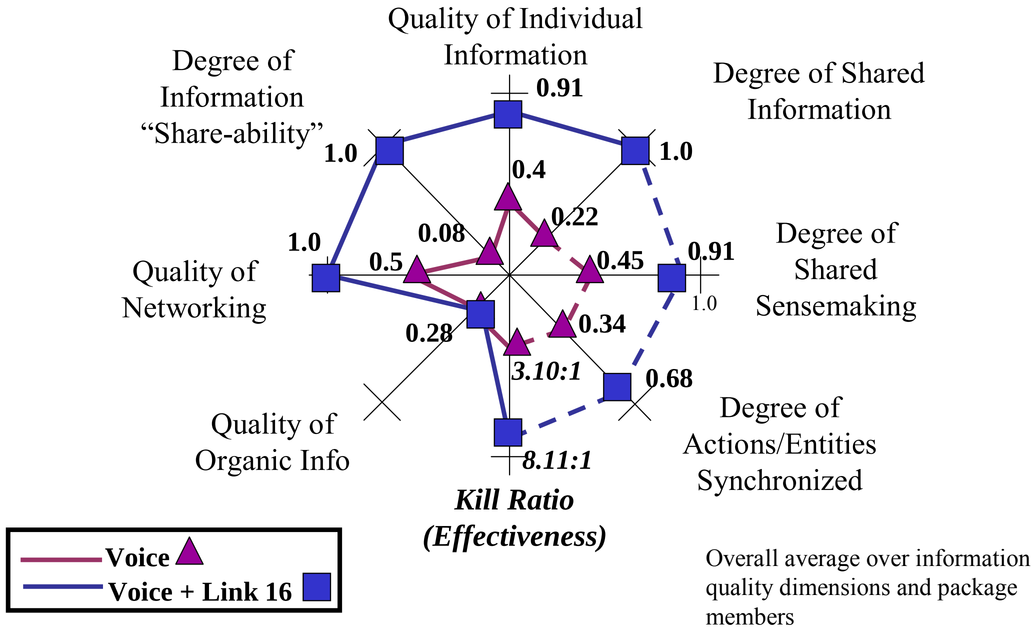


Figure 6: Normalized NCO-CF metric scores for the JTIDS Air-to-Air study, (Garska and Alberts, 2004:70).

RAND also noted that, while the Air-to-Air case was a good starting point for using the NCO-CF, "it did not stress the NCO CF in a number of areas that should be addressed in future studies" (Gonzales and others, 2005:79). For example, they cited the simplicity of the scenarios and low number of entities involved hindered the evaluation of how the information regarding command intent would have been handled, for example. RAND recommended the NCO-CF be applied to several, more complex case studies to continue maturing the metrics.

They also recommended that several variables be considered for inclusion in later versions of the framework. These variables included training, tactics, procedures, size of the network, quantity of organic information, and information fusion processes (Gonzales and others, 2005:79).

2.6.3 Complex Military Command and Control Networks

David A. Jarvis of Alidade Incorporated recognized the importance of analyzing military networks as a complex system and the possibilities of applying the science of networks to command and control systems. In his "discovery analysis" paper, "A Methodology for Analyzing Complex Military Command and Control (C2) Networks," Jarvis applied structured network measures to a vital part of modern command and control system, the electronic mail network. For command and control, the e-mail reveals much about the social structure of warfare in the Information Age. Specifically,

> The goal for the C2 network analysis was by analyzing the structure, dynamics and evolution of the email network employed by coalition participants, lessons on how to design adaptive command and control structures that are robust and match natural usage patterns could be derived (Jarvis, 2005:5).

Jarvis states, based on previous studies, e-mail patterns can reveal insights into an organization's informal and formal structures, and vulnerabilities. Since the execution of C2 is people-intensive, understanding these structural network issues would be a valuable tool in improving C2.

Using e-mail traffic data from a combined United States (US) and United Kingdom (UK) naval exercise, Jarvis first constructed graphs of the network that reflected e-mail traffic over the course of the exercise. Each vertex represented one e-mail address, parsed from the "To:", "cc:" or "Sender" fields of the e-mail header. Each edge was directed with the starting point at the sender address and the ending point at the receiver, resulting in a directed graph.

To address the dynamic aspect of the analysis, the e-mail data was divided into timeframes of six hours apiece over 24 hours starting at 0000 hours, correlating to the battle rhythm of the exercise. The data from each timeframe provided a graph representing a snapshot of the e-mail network for that time period. Dynamic characteristics were extracted by first extracting structural network characteristics from each graph and then plotting those characteristics over time.

Jarvis's "essential elements of analysis" centered around five questions. The metrics used in his analysis are often used in complex network analysis. Table 2 summarizes the questions and the corresponding metrics used to support answering them.

Table 2: C2 Elements of Analysis and Metrics, (Jarvis, 2005:6).

Essential Element of Analysis	Question	Metric
1	Does the introduction of new e-mail software tools change previously established operating procedures?	• Link/node ratio • Degree distribution • Characteristic path length
2	Who are the key nodes for e-mail traffic flow?	• Identify hubs • Clustering coefficient • Betweenness centrality
3	How robust is the e-mail network in light of the removal of nodes and/or links?	• Betweenness centrality • Characteristic path length
4	How does the structure of the e-mail network evolve over the course of the exercise?	• Graphic visualizations of network structure at different time periods during the exercise • Select metrics over time
5	What are the internal dynamics of select sub-networks and how do the sub-networks interact with each other?	• Graphic visualization of the sub-networks over the entire exercise • Nucleus/fringe nodes

Several conclusions resulted from this analysis. From a network analysis perspective, Jarvis was able to categorize the e-mail network of the US/UK exercise as a "scale-free" network. Such networks have a few vertices that act as "hubs." Like airport hubs, these vertices have many connections (edges) to other vertices and become the center of activity. The majority of the vertices have much fewer edges. The implications of this network structure led the US Navy to recommend several courses of action to include implementing improved defenses for the most important C2 hubs.

The dynamic network analysis also yielded interesting conclusions. The increase and decrease of activity during certain timeframes of the exercises provided insight to improve resource allocation, not only in network throughput but personnel. At one point, the analysis showed that the intelligence office and the commander positions consistently received an abundance of e-mail traffic. This could be an indication of overworked positions. One of the Navy's courses of action in this area was to "support decision of critical nodes placement in distribution of staff" (Jarvis, 2005:20).

Using this analysis, representatives from the Navy Warfare Development Command (NWDC) and Navy Warfare Network Command (NNWC) recommended nine courses of action. The actions were under the areas of Information Operations and Information Assurance, C2 Structure and Information Flow, and Network and Information Management.

Jarvis's paper demonstrated that using complex network analysis of C2 networks reveals vital insights into those networks. Applying this methodology to analyzing NCW theory seems to be a viable extension. The e-mail network was just one segment of a larger C2 network (Jarvis, 2005:21). If a model of NCW incorporated people, processes, and technology were analyzed in the same vein, valuable insights could be revealed.

2.7 Layered Complex Graphs

The topology or structure of a network is very important to determining the performance of that network. But how can one represent this relationship between the network and the activity utilizing the network?

One solution was proposed by Maciej Kurant and Patrick Thiran of the Ecole Polytechnique Fédérale de Lausanne. They noted results from traditional analysis of the loading of transportation networks did not accurately reflect actual loading behaviors. Realizing that certain transportation system may be classified as complex system, they developed a model of such networks that should yield more accurate results.

In their paper, "Layered Complex Networks," Kurant and Thiron model the influence that networks have on each other another by superimposing, or "mapping" one network topology onto another. Capturing this relationship facilitates a more accurate representation of complex networks since networks in a complex system may have effects on other networks besides their immediate network. Kurant and Thiran called their model a "multilayer model," and applied it to studying European rail systems.

Kurant's and Thiran's describe their multilayer model with the following node and edge relationships. For simplicity, only a two-layer relationship is used. The model, as will be seen, may be extended to multi-layers. The lower-layer topology is called a physical graph, $G^{\varphi} = (V^{\varphi}, E^{\varphi})$, and the upper-layer is called the logical graph, $G^{\lambda} = (V^{\lambda}, E^{\lambda})$, where V and E denote the set of vertices (or nodes) and edges, respectively, in graph G. Further inspection of their methodology concludes that this assumption is not a requirement in the multilayer model because any vertices not included in the mapping were basically transparent to the analysis. The number of nodes, N, were also equal for both layers, that is $N= |V^{\lambda}| = |V^{\varphi}|$ (Kurant and Thiran, 2006:1).

Every logical edge, $e^{\lambda} = (u^{\lambda}, v^{\lambda})$, where u and v are vertices in G^{λ}, is mapped on the physical graph G^{φ}, as a physical path $M(e^{\lambda}) \subset G^{\varphi}$, connecting the nodes u^{φ} and v^{φ}, corresponding to u^{λ} and v^{λ}. The collective set of paths is called the mapping $M(E^{\lambda})$ of the logical topology on the physical topology. The relationship which governed which particular edges are mapped to each other is determined by the analyst and the relation of the topologies of interest (Kurant and Thiran, 2006:1).

They applied the multilayer model to study the dynamics of rail traffic for rail systems ranging from the city of Warsaw, Poland, to the entire continent of Europe. Kurant and Thiron's hypothesis was that using this model would yield higher fidelity data when applied to the problem of loading of transportation networks.

Kurant and Thiron designated the train tracks between stations as the set E^{φ} of the physical layer, G^{φ}. The logical edges, E^{λ}, were the "lines" connecting the initial departure and final destination of a specific train route. The train stations became the vertex sets, V^{φ} and V^{λ}. For example, the mapping of a train route, e^{λ}_1, onto G^{φ} resulted in a path, $M(e^{\lambda}_1)=(v^{\varphi}_1, v^{\varphi}_2, v^{\varphi}_3)$. The complete mapping of all edges, E^{λ}, would result in a set of paths, M.. For their analysis, they also applied edge weighting to represent different levels of loading. The graphs in this model may also be bi-directional. Figure 7 shows the layered model and corresponding rail systems studied by Kurant and Thiran.

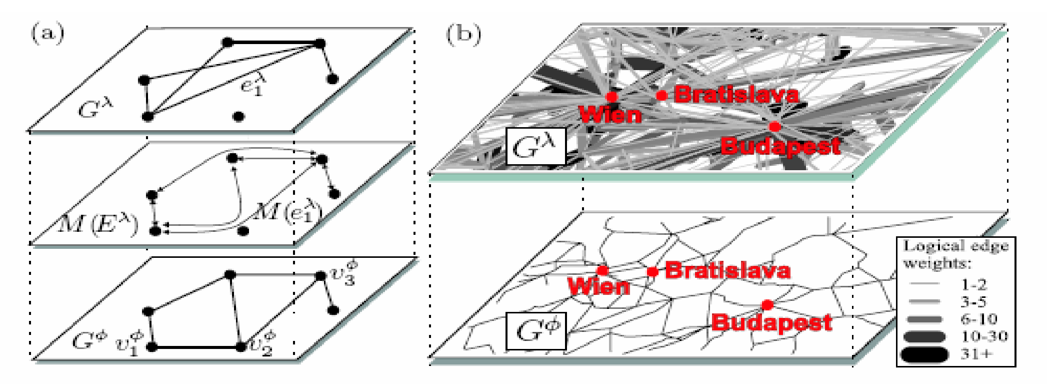


Figure 7: Illustration of Layering Graphs, (Kurant and Thiran, 2006:2).

Further information on this analysis can also be found in "Trainspotting: Extraction and Analysis of Traffic and Topologies on Transportation Networks," by the same authors. For the purpose of this thesis, only the multilayer model and mapping concept will be applied.

2.8 Joint Expeditionary Forces Experiment (JEFX) 2006

The Joint Expeditionary Forces Experiment (JEFX) is one of the major venues with which the DoD conducts experiments with emerging C2 technologies and procedures and evaluates systems for rapid acquisitions and fielding. The JEFX program is led by Air Force Experimentation Office at Langley AFB, VA partnered with the 8thAF from Barksdale, LA and AF Component Commander, United States Strategic Command, Offut AFB, NE. Major stakeholders and teams nation-wide include Hanscom AFB, MA and Nellis AFB, NV.

The first Expeditionary Forces Experiment was held in 1998. Experimental events have been executed every year. JEFX, the major event is held biennially in the even years and the smaller Advanced Process and Technology Experiment (APTX) occurring in the odd years. APTX serves as risk reduction and focuses on smaller concepts that support the JEFX of the following year.

JEFX combines many elements to represent the warfighting environment. Live military assets are incorporated, termed "live-fly" participants, while other areas are simulated through an extensive modeling and simulation architecture. For JEFX 06, approximately 39 live aircraft were used with over 40 models and simulations. With the JV2020 emphasis on joint and coalition warfare and the need to conduct experiments in an environment that keeps close integrity to real-world operations, JEFX participants include joint, coalition, and allied participants.

JEFX 2006 assessed eight new technology initiatives. The processes were designed to increase command and control capability, enhance predictive battlespace awareness, and decrease the time it takes to find, fix, target, track, engage and assess a given target (Tweten, 2006:1).

The initiative supported operational threads that were executed during the experiment. For the purpose of this thesis, the following threads were used in the analysis:

1. Prosecute Time Sensitive Targets (TST): Streamline TST process via improved processes and advanced technologies (AFEO, 2006). For analysis purposes, the label "Pro TST" will be used for this thread.

2. Enhance C2 SA with Non-Traditional Intelligence, Surveillance and Reconnaissance (NTISR): Explore the suitability of an airborne tactical IP network as a homogeneous extension of a terrestrial-based C2 network by presenting NTISR (from an armed manned platform) of time critical target scenes to intelligence and operations duty officers and stress their ability to harness the netcentric targeting, decision, and execution applications available to them to command prosecution of the target (AFEO, 2006). For analysis purposes, the label "C2 SA" will be used for this thread.

3. Prosecute NTISR: Initiate an NTISR mission and assess the tasking, collection, exploitation, and dissemination process (AFEO, 2006). For analysis purposes, the label "NTISR" will be used for this thread.

III. Methodology

3.1 The Multi-layer Model of Network Centric Operations

Given the discussion of the science of networks, graph theory, and NCO, how would one proceed to incorporate these ideas into the NCW-CF? To begin, a multi-layer model of NCO, as depicted in Figure 8, is proposed.

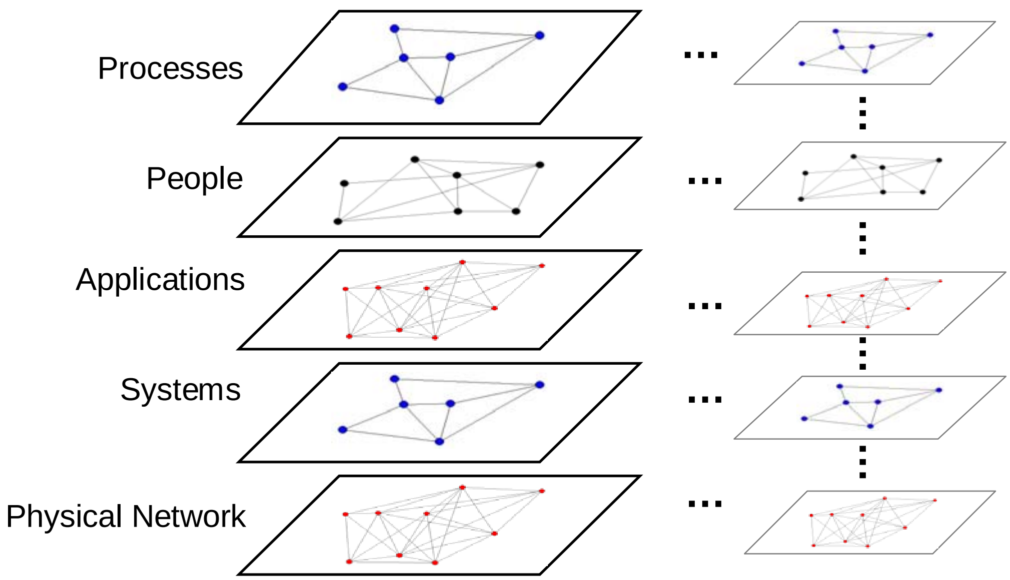


Figure 8: Layered model of Network Centric Operations

In the multi-layer model, each family of contributor to NCO is designated as a layer. Thus, People, Applications, Systems, etc, each play a part in the success of some Process that supports NCO. At each layer, the family of contributor is represented graphically as a network. The nodes represent individual contributors and the edges between them represent a layer-specific relationship. Table 3 defines the nodes and edges representation of each layer.

Table 3: Layer, Node, and Edge Definitions for the Multi-layer NCO Model.

Layer Name	Layer Definition	Node Definition	Edge Definition
Processes	Series of tasks in the process of interest that lead to a mission objective. These processes are based on higher level guidance, such as doctrine or ROEs.	Each node represents one task in the series of tasks.	Edge between tasks represents the transition of one task to another. By default, the edge also represents the order in which the tasks are accomplished. A node can have multiple edges if tasks are accomplished concurrently.
People	Actors that perform tasks	Each node represents a person or a group of persons.	Edges between persons represent working relationships where specific information is sent or received. A "human network."
Applications	Tools that send, receive, and/or process information. These tools may be automated or require an operator interface.	Each node represents an application. A separate node may be used to designate one copy of an application if multiple copies exist in the network of interest.	Edges between applications represent data-specific interoperability between systems. The edge is specific to the data that is passed, since systems may be partially interoperable.
Systems	Platform which houses the application(s) (i.e. an aircraft platform could be grounded but its Applications may still function.)	Each node represents a system.	Edges between systems represent communications interoperability.
Physical Network	Communications infrastructure.	Each node represents routers, servers, radios, etc.	Edges between nodes represent communications pathways. These edges include both wired and wireless pathways.

3.2 Layer Interrelationships

The purpose of choosing this layering scheme is to establish a cohesive set of relationships for the major entities, that is, people, processes, technologies, contributing to NCO. The layering hierarchy is based on the most direct interactions between major groups of entities. For example, mission level objectives are executed through a series of processes. The successful accomplishment of these processes is a measure contributing to mission accomplishment. The most direct influence on the completion of a process is the people that perform them.

Regarding the interrelationship of people and applications, people are the most direct users of applications to process and share information and to collaborate.

Machine-to-machine (M2M) applications exist, but the initiation of the process which called for using the M2M application was begun at some point by a person.

Additional layers may be defined and added horizontally or vertically to the model, as depicted in Figure 8. In effect, this would establish a graph of graphs with many to many relationships within and between layers. The analysis procedures discussed later will still apply. However, it is important to provide distinct definitions for what each layer and their interrelationships represent.

As such, this model shows that any failures or successes that occur at the lower layers may contribute (negatively or positively) upon the completion of mission objectives. A summary of the interlayer relationships is shown in Figure 9.

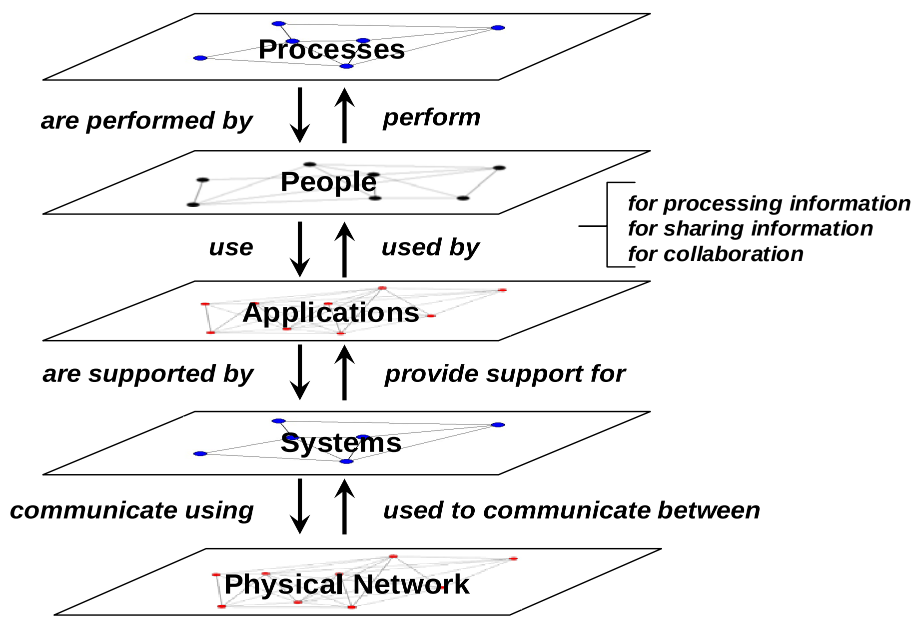


Figure 9: Interlayer relationships of the Multi-layer NCO model

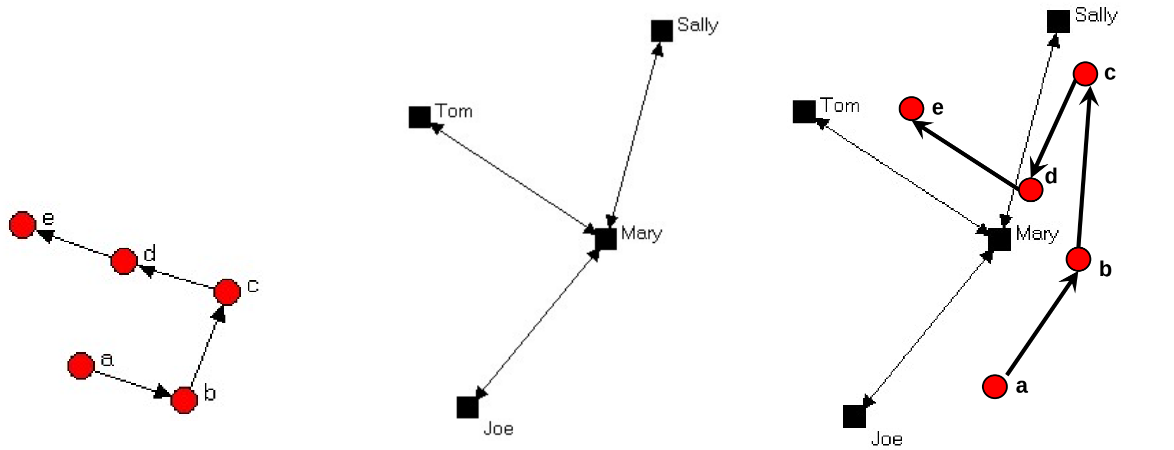
For this model to be useful for analysis the interlayer relationships must be further defined and a representation for these relationships must be established. Like the node and edge definitions in Table 3, the interlayer relations also have definitions relevant to NCO. These definitions are found in Table 4.

Table 4: Definitions of Interlayer Relationships of the Multi-layer NCO model.

Mapping	Node to Node Mapping	Edge to Edge Mapping
Process-People	Allocates task to person(s)	Order or route of process tasks through people
People-Applications	Identifies the applications used by person(s)	Route of information transactions through applications
Applications-Systems	Identifies which systems support which applications. For some, the system and application are the same.	Route of information from application to application through supporting systems. For cases where multiple applications are supported by one system, there may be edges from the application layer that "roll-up" into a system node and do not exist on the mapping.
Systems-Physical Network	Identifies which entry points into the communications infrastructure is accessed by which system	Route of communications from one system to another. From a wireless communications perspective, this could represent the route of data transmitted from an aircraft via a radio to a ground node to a radio and back to another aircraft's radio through the physical infrastructure..

The following discussion further describes the concept of interlayer relationships, beginning at the Process Layer. Figure 10 illustrates the example by showing how Process and People layers and the instantiation of their interlayer relationships through the process of mapping. Given a process, Figure 10(a), which is based upon doctrine, Rules of Engagement (ROEs), Tactics, Techniques and Procedures (TTPs), etc., the process's tasks are allocated to the person or group of persons, Figure10(b), responsible for accomplishing the task(s).

In general, the process of "allocating" will be termed "mapping." The intermediary layer between the process and people layers is termed the "process-people mapping" as shown in Figure 10(c). The tasks of a process are "mapped" to the person doing that task. Using graph theory terms, the task nodes are mapped to the person nodes. The process layer edges, when mapped to the people layer, show who acts first, second, and third,



(a) Process Layer (b) People Layer (c) Process-People Mapping

Figure 10: Mapping Two Layers

etc., as the tasks are completed. The process-people map will reflect “who did what” and “when”. In this context, “when” is meant as “Joe does ‘a’ before Mary does ‘b’,” not a specific place of time.

More specifically, the process layer, Figure 10(a), uses a graph to show a sequential process with five tasks, ‘a’, ‘b’, ‘c’, ‘d’, and ‘e’. The tasks are performed in the following order: first ‘a’, then ‘b’, etc., ending with task ‘e’. The arrows help depict this order. Hence, the process layer is a directed graph.

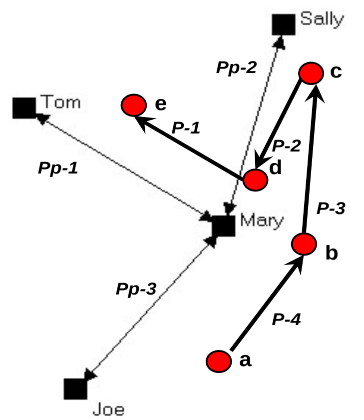
The people layer in Figure 10(b) shows four people who engage in a working relationship. This graph is bi-directed--the edges can be traversed in either direction. In the context of human behavior in a working environment, if Joe works with Mary, then it is assumed that Mary also works with Joe. This graph also depicts that certain persons do not work with each other. For instance, Tom and Sally do not work together directly.

The process-people mapping, Figure 10(c), shows the nodal mapping as well as edge mapping. From a nodal perspective, the graph shows that Joe is responsible for task 'a', Mary does task 'b', and so on. As depicted, Mary is actually responsible for two tasks, 'b' and 'd.' The edge mapping shows the order or "route" of the process as it progresses through the responsible persons. While each layer provides information about each homogenous entity, the mapping provides a graphical representation of the interaction and relationships *between* the entities.

To perform the analysis, each layer and mapping is represented by a series of matrices. Both adjacency and incidence matrices are used. To accomplish the mapping, two matrices are used. One correlates the vertices of one layer to desired vertices of another layer. Likewise, the edges of both layers are correlated. The individual vertices or edge mappings may then be combined into a comprehensive vertices or edge mapping matrix. The comprehensive mapping matrices then served as the model-wide mapping, up and down the stack of layers. This comprehensive mapping vertices matrix is then used to trace the all vertices associated with one vertex throughout the entire model. The same occurs for the comprehensive edge matrix. Thus, a vertex or edge at any layer of the model may be altered and the effects of that alteration may be traced throughout the other layers. The column and row labels are duplicated because this allows traceability of each node or vertex. Continuing with the example in Figure 10, Figure 11 illustrates how the comprehensive vertex and edge matrix for two layers would be constructed. Edge labels have been added.

	Tom	Mary	Joe	Sally	a	b	c	d	e
Tom	0	0	0	0	0	0	0	0	**1**
Mary	0	0	0	0	0	**1**	0	**1**	0
Joe	0	0	0	0	**1**	0	0	0	0
Sally	0	0	0	0	0	0	**1**	0	0
a	0	0	**1**	0	0	0	0	0	0
b	0	**1**	0	0	0	0	0	0	0
c	0	0	0	**1**	0	0	0	0	0
d	0	**1**	0	0	0	0	0	0	0
e	**1**	0	0	0	0	0	0	0	0

(a) Comprehensive Vertices Mapping Matrix



(c) Process-People Mapping

	P-1	P-2	P-3	P-4	Pp-1	Pp-2	Pp-3
P-1	0	0	0	0	**1**	0	0
P-2	0	0	0	0	0	**1**	0
P-3	0	0	0	0	0	**1**	0
P-4	0	0	0	0	0	0	**1**
Pp-1	**1**	0	0	0	0	0	0
Pp-2	0	**1**	**1**	0	0	0	0
Pp-3	0	0	0	**1**	0	0	0

(b) Comprehensive Edge Mapping Matrix

Figure 11: Comprehensive Vertices and Edge Mapping Matrices, (a) shows mapping of vertices to vertices, (b) shows mapping of edges to edges, and (c) the graphical depiction of the mappings.

3.3 Advantages of the Multi-Layer NCO Model

The advantages of this layered model are the following:

1. Network analysis metrics may be applied at any level, allowing each layer to be analyzed
2. The mapping between layers allows the traceability of cause-and-effect from either bottom-up (i.e. effect of loss of people on the completion of the process) or top-down (i.e. consolidation of application on the type of platform supporting it.
    a. Consideration for the complexity of relationships at each layer and between layers is incorporated.
3. Upholds and provides additional insight to the concepts in the NCO-CF

a. Upholds the NCO-CF Value Chain concept (Garska and Alberts, 2004:63)

b. Serves the intended audience of the NCO-CF ("applications such as case studies, experiments, or specific acquisition decisions a more detailed and complex representation (Garska and Alberts, 2004:64)

4. Integrally accounts for the accomplishment of commander's intent via the processes layer into the model. Thus, objective operational effectiveness measures on completion of processes can be made to support assessments

5. Allows flexibility for the audience to determine the amount of detail at each layer. Layers, vertices, and edges may be defined to suit the level of analysis desired.

6. When vertices and edges are specifically labeled, commanders can trace the specific effect to a cause in the NCO system as a whole.

3.4 Analysis Using the Multi-Layer NCO Model

The layered model, coupled with the above metrics, produces a holistic view of the networks involved for the successful execution of a mission objective at the Process layer.

Individual nodes/edges. For the metrics that apply, node and edge characterizes are produced, allowing a detailed look at each contributor to the network.

Individual layer. The network at each layer produces characteristics which can be collected into a composite view as shown in Figure 12. A radar chart is used to depict this view. Each layer is then assigned a composite network score, $N_{layer,}$ which is calculated by normalizing the area under the curve of the radar graph.

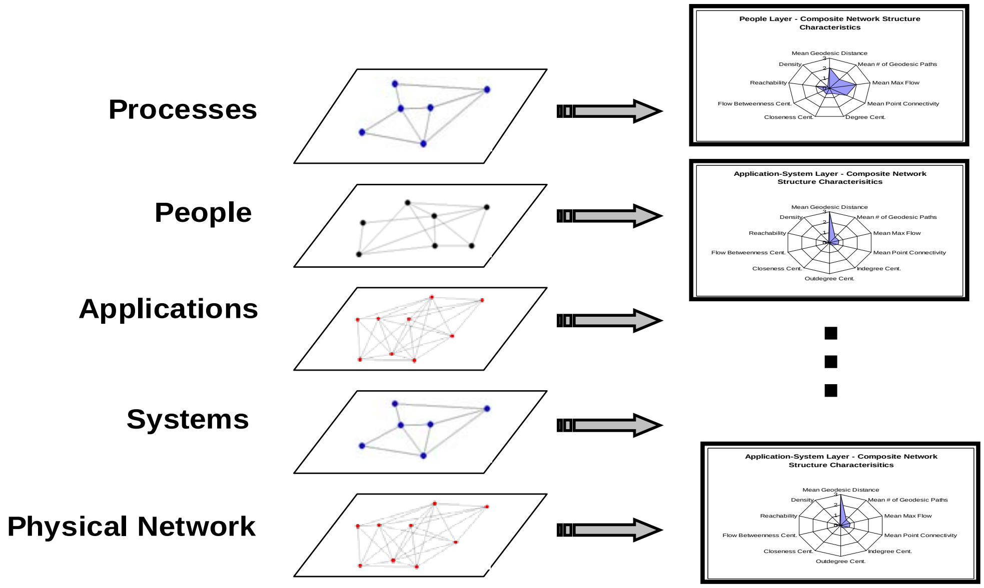


Figure 12: Each network layer's structure is represented by a composite graph of its characteristics.

<u>Network Centricity Score.</u> The network centricity score, NC, provides a holistic score for all the layers. For i layers, $NC = \prod_i N_i$. The initial NC score may be used as a baseline. When changes are made to any layer(s), the recalculated NC score will indicate the relative merit of those changes. While the approach in this thesis used the same characteristics for all layers, this uniformity is not required.

<u>Mission Effectiveness.</u> The mapping of the layer interrelationships produces a traceability of cause and effect, as discussed earlier. The measure of mission effectiveness resides at the Process layer, since the lower layers support the completion of a process. Fundamentally, mission effectiveness will be low if the majority of a process is incomplete or fragmented. Likewise, mission effectiveness will be generally higher if more of a process is successfully completed. As defined, the Process layer consists of tasks (nodes) and transitions (edges). Both the task and transition must be accounted for in this measure because a task may be completed but not successfully transitioned to the next task, i.e. "the results of the previous task never got passed on." Therefore, the degree of mission effectiveness could be expressed as the sum of the ratio of tasks and edges completed.

3.5 UCINET

The tool used for much of the network characteristics calculations is Analytic Technologies' UCINET 6 software. UCINET 6 is a comprehensive program for the analysis of social networks and other proximity data. The program contains dozens of network analytic routines. It's library of analysis features include centrality measures, positional analysis algorithms, and stochastic dyad models. In addition, UCINET can perform general statistical and multi-variate analysis such as multi-dimensional scaling and cluster analysis. UCINET provides a host of data management and transformation tools ranging from graph-theoretic procedures to a full-featured matrix algebra language (Borgatti and others, 2006:1).

UCINET uses matrices to store and manipulate data. The user is encourage to understand that, while many of the above procedures may use terminology that is specific to that procedure, understanding that UCINET's underlying structure is based on matrices will help to understand how the tool works (Borgatti and others, 2006: section 0.4).

3.6 Extending the Network Centric Operations-Common Framework

The NCO-CF incorporates the four tenets of NCW,

1. A robustly networked force improves information sharing
2. Information sharing enhances the quality of information and shared situational awareness

3. Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command
4. These, in turn, dramatically increase mission effectiveness (OFT, 2005:7).

The NCO-CF also incorporates the spectrum of the DOTMLPF into "top-level concepts." These concepts are designed to assess Degree of Networking, Degree of "Information Shareability", Quality of Interaction, and Degree of Actions/Entities Synchronized, to name a few. However, improvements can be made to further the usefulness of the NCO-CF to a variety of audiences to include the military commander.

The CF measures several domains which, at this point in the CF evolution, rely on subjective data. While this information may prove useful, the subjective nature of this metric does rely on participants' input, which can introduce challenging uncertainties into the NCW analysis. For example, the concept of Degree of Effectiveness has an attribute titled Achievement of Objectives. This attribute is defined as "degree to which strategic and political/military/social/etc. objectives were achieved" (Garska and Alberts, 2004:96). This measure has a scale of one to five, "1 = intent was not achieved, 5 = intent was achieved" (Garska and Alberts, 2004:96). If this attribute was measured with a network structure perspective, the metric would become more objective and repeatable.

As described earlier, network theory and complex systems acknowledge that entities in a network influence the characteristics of that network. In the case of NCW, people, processes, applications, systems, the physical network (routers, servers, etc.), are all related because each entity uses, relies upon, or performs the other. "People perform steps in a process." "People use applications." "Systems rely on the physical network to send data." These are some of the relationships that can be made between the entities. The entities also have relationships with other similar entities. In the physical network, routers, and servers may be connected by cable or wirelessly. People are connected to each other by social networks.

By incorporating graph theory-based metrics into the framework, the NCO-CF will be extended to gain objective insight into the overall characteristic(s) of the people, processes, and technology networks that work together to enable NCO. For example, the NCO-CF measures the attribute, Extent, under the concept Degree of Shared Information. Extent is defined as "the proportion of information in common across force entities and the proportion of force entities that share an information item" (Garska and Alberts, 2004:109). The metric is the percentage of force entities that share an information item. This metric is helpful to track because it "measures the proportion of information that is held in common across force entities" (Garska and Alberts, 2004:108). A high level of shared information can lead to better collaboration between entities and also shared situational awareness. In short, the information is traversing the network. However, characterizing the underlying structure of the network may explain a certain Extent score. Perhaps reconfiguring the network structure by adding or deleting connections could improve the Extent score. In this light, such value-based insight would also contribute to the actual design of the network itself. Augmenting Degree of Shared Information and other top-level NCW concepts with network theory characteristics and structure data would provide further insight into not only the evaluation of this aspect of NCW, but to it's overall implementation.

Table 5 correlates network theory-based metrics to current NCO-CF metrics show the how current NCO-CF metrics may be extended.

Table 5: Summary of NCO-CF Metric Extensions

Top-level NCO-CF Concept	Attribute	Attribute Definition	NCO-CF ver 2 Metric	Extension Metric
Degree of Effectiveness	Achievement of Objectives	- Degree to which strategic and PMESII objectives were attained. - Degree to which strategic and PMESII objectives were attained	Scale 1-5	- Degree of Effectiveness based on Layered Model, DoE.
Quality of Networking: Degree of Networking	Reach	- Number of force elements on the net	Percent of nodes that can communicate in desired access modes, info formats and applications	- Reachability - Maximum Flow - Point Connectivity
Quality of Networking (II): Degree of Networking: Agility	Robustness:	- Effectiveness of network across a range of operational conditions	Number of differing conditions/environments over which the network is capable of operating at a given level of effectiveness	- Reachability - Maximum Flow - Point Connectivity
	Resilience	- Ability of network to perform effectively despite attacks and/or perturbations	Number and type of nodes removed before degradation in QoS occurs Note: time to loss of QoS will not be considered in this analysis.	- Flow Betweenness
Degree of Shared Information	Extent	- Proportion of info in common across force entities, proportion of force entities that share info item	Percentage of force entities that share an information item	- Geodesic Distance - # of Geodesic Paths - Reachability - Freeman Degree Centrality - Closeness Centrality
Quality of Individual Sensemaking: Individual Awareness				- Additional Metric: Capability of Network Layer to Spread Awareness. Based on composite network score, N_{layer}
Degree of Shared Sensemaking: Shared Awareness				- Additional Metric: Capability of Network Layer to Spread Awareness. Based on composite network score, N_{layer}
Degree of Shared Sensemaking: Collaborative Decisions (I)	Extent	- Proportion of force entities that reach a collaborative decision	Percentage of C2 elements participating in a collaboration	- Additional Metric: Capacity of Network Layer for Collaboration. Based on composite network score, N_{layer}

In general, extending the NCO-CF with quantifiable metrics, which in turn contribute to measuring the baseline network structure, N_{layer}, would be beneficial to understanding if the network is capable of executing a desired activity. The inclusion of an N_{layer} measure provides objective, network-oriented insight. An overall net-centricity measure, NC, then provides a holistic roll-up measure.

3.6.1 Definition of Metric Terms

The following terms and metrics will be used in the NCO analysis. The metrics also are supported by UCINET. Following each definition is a discussion of the possible implication of that metric to NCO analysis, tying the metric's theoretical meaning to the practical application. These metrics will be used to objectively extend the current NCO-CF. While the term "vertex" is used in the formal, graph theoretical definitions, the term "node" will be used throughout the majority of the analysis because of its common use in network analysis. Further discussion of each metric can be found in Robert Hanneman's and Mark Riddle's on-line book, *Introduction to Social Network Methods* (Hanneman and Riddle, 2005)

Out-degree, $d^+(v)$.

Definition: For a directed graph with vertex v, $d^+(v)$ is the number of edges with tail v (West, 2001:58).

NCW Implication: A vertex serves as an information source within a network. From a collaboration viewpoint, a vertex with a high $d^+(v)$ may indicate network node with a high level of collaboration with the nodes around them and carries a greater potential to influence its neighbors and the rest of the network. For example, should this node pass inaccurate data into network, more nodes would be effected than if a node with lower $d^+(v)$ had passed on that data. Referencing the layered NCW model, at the People layer, this node may characterize a commander's position as a commander may be giving orders to multiple supporting commanders. At the Process layer, such a node may indicate that many processes rely on this task in order to proceed.

In-degree, $d^-(v)$.

Definition: For a directed graph with vertex v, $d^-(v)$ is the number of edges with head v (West, 2001:58).

NCW Implication: A vertex serves as an information sink within a network. A vertex with high $d^-(v)$ may be a critical convergence point for some activity. A high $d^-(v)$ may also be a sign of potential information overload or, since it receives many different inputs, it may be a potential point of conflict. At the Application layer, a node with high $d^-(v)$ may indicate an application that may benefit from an improvement to its data processing functions to increase efficiency.

How does one interpret a vertex with both high in- and out-degree? This vertex may be a bottleneck to the overall operations or could benefit from improvements to increase efficiency. For example, these improvements could be increased manning at the People layer, increased automation at the Applications layer. On the other hand, perhaps certain routing or switching systems may also exhibit these characteristics by design.

Density, d(G).

Definition: The ratio of the number of edges to number of vertices (West, 2001:435, 519). For a graph G with number of vertices, n, and number of edges, e, the density of G is $d(G) = \frac{e(G)}{n(G)}$.

NCW Implication: For the System layer, the measure of an N-node network's "N^2-connectedness" would be the density. In "Power to the Edge", the N^2 approach is an ill-fated solution to system interoperability in which system A can be interoperable with all other systems if system A understands the same language, protocol, etc., with every other system. This scheme would hold true for every system in the network, resulting in a network where every system must be connected to every other system to communicate across the network. This approach results in a very unsustainable network. Measuring density at the System layer would provide a quantifiable network characteristic.

Reachability.

Definition: A value, "1" or "0," for each vertex pair (u, v) in graph G if there is a path from u to v. The value is "1" if a path exists, "0" if it does not (Borgatti and others, 2006:142). The reachability metric has a very close correlation with distance. For a directed graph, this metric indicates the possibility of a flow between u and v.

NCW Implication: Reachability at all layers indicates if there are any unconnected nodes in the network. Reachability at the Applications, Systems and Physical Network layers can also be an indication of the level of interoperability. A fully interoperable network would earn value "1" between every pair of nodes. A network may be considered "weak" if few nodes are reachable from few others, "strong" if many nodes are reachable from many others.

Point Connectivity.

Definition: The size of the vertex cut of graph G between two non-adjacent vertices, u and v. The vertex cut is defined as the smallest set $S \subseteq V(G)$, such that (G-S) has more than one component (West, 2001:149). The point connectivity is another term for the size of the vertex cut.

NCW Implications: For any layer, point connectivity indicates vulnerability of a network between two nodes of interest. For instance, if the point connectivity of node A to node B is three, there are three nodes whose removal would completely disrupt the communication between A and B. Inspection of the network graph would reveal those three specific nodes and a course of action can be developed to prevent any disruptions. Though point connectivity does not explicitly indicate the nodes that compose the vertex cut, it can point to potential problem areas.

Distance, d(u, v).

Definition: The minimum distance of the path from vertex u to vertex v (West, 2001:70,520), also known as the geodesic distance. Distance is measured by summing the value of each edge connecting each internal vertex along the (u,v) path. The value used here is one, but may be weighted with other values depending on the context of the graph. For instance, if the edges represented physical distance, the value of each edge may represent mileage between vertices. This metric is an important macro-characteristic, because it analyzes each possible path across the network between each u and v for all u and v.

NCW Implication: At the People layer, a high d(u,v) may reflect the reach of the circle of influence or social network of person A. (Hanneman, 2006) If person B is d(u,v) = 2 away from person A, he/she is "someone who knows someone who knows person A." Person A's influence is further diluted as d(u, v) increases. The exertion of influence is important both to passing on commander's intent as well as collaboration between persons. At the Application layer, a high d(u, v) may indicated that data originating from application A is undergoing d transformations before it is finally usable by application B. At the System layer, long distances may indicate a lack of communications interoperability, if the message being sent from system A must be translated by protocol gateways at each intermediate platform before the destination system can accept it. At the Physical layer, a long distance between nodes may indicate a longer overall network delay as data packets travel through the infrastructure. In all these cases, the distance metric may be used to streamline for increased efficiency at each layer.

Number of Geodesics.

Definition: The number of shortest paths connecting any pairs of vertices (Borgatti and others, 2006:141).

NCW Implication: This metric is a measure of redundancy at any layer of the NCW model. Multiple paths indicate that two nodes have several ways of reaching each other.

Maximum Flow.

Definition: In a graph, the value of each edge can represent a capacity. Let c(x) denote the capacity of each edge x of a graph G. A flow in G between two nodes s and t is a function f such that $0 \leq f(x) \leq c(x)$ for every edge x. The maximum flow between s and t is the sum of the flow along all paths leaving s and arriving at t (Borgatti and others, 2006:143).

NCW Implication: For every layer, maximum flow reflects the network-wide connectivity, or strength of overall connections, between two nodes. However, the meaning of that connectivity varies for each layer. At the People layer, maximum flow contributes to the maximum collaborative reach between two persons. For example, if person A issues an order to all his/her neighbors and those neighbors pass that order on, the maximum flow at person B will be the sum of all the previous connections that order passed through before it reached person B. The greater the value of the maximum flow, the greater the number of persons across the entire network that received that order. For the Application, System, and Physical layers, the maximum flow is a network-wide snapshot of how widely information could be disseminated throughout the network.

Network Centrality. The concept of network centrality comes from the study of network structure and the desire to understand how the relative placement of a node in a network may inherently constrain or aid the node's behavior. There are three basic facets of centrality, or network placement: degree centrality, closeness centrality, and betweenness centrality.

Freeman Degree Centrality.

Definition: For a vertex v in a directed graph G, the in-degree centrality is $d^+(v)$ and the out-degree centrality is $d^-(v)$. For a bidirectional graph, the degree centrality of v is simply the degree of v, d(v). The degree centrality reflects the direct relationships of a node with others in a graph adjacent to it (Borgatti and others, 2006:167).

The network centrality based on degree is also a useful metric. It provides the measure of variability of the degree centrality across the entire network as measured against an ideal star network of the same size. The degree centrality, $c(v_i)$, is the degree divided by the maximum possible degree expressed as a percentage. For a given network with vertices $v_1....v_n$ and maximum degree centrality c_{max}, the network degree centralization measure, defined for all vertex i, is $\sum(c_{max} - c(v_i))$ divided by the maximum value possible, where $c(v_i)$ is the degree centrality of vertex v_i (Borgatti and others, 2006:167).

NCW Implication: See in-degree and out-degree.

Betweenness Centrality.

Definition: Let b_{xz} be the proportion of all geodesics, g, linking vertex x and vertex z which pass through vertex y, $b_{xz} = \frac{g_{xyz}}{g_{xz}}$. The betweenness of vertex y, b_y, is the sum of all b_{xz} where x, y and z are distinct, $b_y = \sum_{x,z} b_{xz}$. Betweenness is therefore a measure of the number of times vertex y occurs on a geodesic.

The betweenness centrality, $c(v_i)$, is the betweenness divided by the maximum possible betweenness expressed as a percentage. For a given network with vertices $v_1....v_n$ and maximum betweenness centrality c_{max}, the network betweenness centralization measure is $\sum(c_{max} - c(v_i))$ divided by the maximum value possible, where $c(v_i)$ is the betweenness centrality of vertex v_i (Borgatti and others, 2006:171).

NCW Implication: In general, for all layers, if a node A has a high betweenness centrality, it has the greater capacity to facilitate or limit interaction between the nodes it links than other nodes (Huang, 2004:2-3). Node A does not have to have a high in- or out-degree to be a critical node under this metric. The criticality of node A is based on which other nodes must use the path that upon which node A lies. From an NCO viewpoint, such a node could become a roadblock or single point of failure. Based upon this criticality, the design of the network at a layer, particularly the Applications, Systems, and Physical Network layers, may require adjustments to address such issues.

Closeness Centrality.

Definition: The closeness centrality of vertex u, c(u), is the sum of geodesic distances to all other nodes in graph G, $c(u) = (\sum_{v} d(u,v))^{-1}$ (Borgatti and others, 2006:169).

NCW Implications: In general, for all layers, closeness centrality measures the ability for nodes to access all nodes in the network more quickly than anyone else. The nodes with highest closeness centrality scores would have the shortest paths to the other nodes. For the People layer, this person may be best positioned in the network to disseminate data quickly to others, assuming the applications layer is optimal. These persons may also be best to monitor others in the network most efficiently. For the Application and System layer, a node with low closeness centrality may signal a node that has low interoperability with other applications and systems.

Edge Betweenness.

Definition: Let b_{ijk} be the proportion of all geodesics linking vertex j and vertex k which pass through edge i. The betweenness of edge i is the sum of all b_{ijk} where j and k are distinct. Betweenness is therefore a measure of the number of times an edge occurs on a geodesic (Borgatti and others, 2006:173).

NCW Implication: In general, for all layers, an edge with a high edge betweenness indicates a critical relationship since many paths contain this edge. For the People layer, this measure will indicate a very important relationship, perhaps one that has a high collaboration potential. For the Application layer, this measure will highlight a critical interoperability link. For the System and Physical Network layer, an edge with high edge betweenness could indicate a more heavily used communications and infrastructure link, respectively.

Flow Betweenness.

Definition: Let m_{ijk} be the amount of flow between vertex j and vertex k which must pass through i for any maximum flow. The flow betweenness of vertex i is the sum of all m_{ijk} where i, j and k are distinct and $j < k$. The flow betweenness is therefore a measure of the contribution of a vertex to all possible maximum flows (Borgatti and others, 2006:177).

The flow betweenness centrality, $c(v_i)$, of a vertex i is the flow betweenness of i divided by the total flow through all pairs of points where i is not a source or sink. For a given network with vertices $v_1....v_n$ and maximum flow betweenness centrality c_{max}, the network flow betweenness centralization measure is $\sum(c_{max} - c(v_i))$ divided by the maximum value possible, where $c(v_i)$ is the flow betweenness centrality of vertex v_i (Borgatti and others, 2006:177).

NCW Implication: For all layers, the flow betweenness is a measure of the possible workload performed by each node if all maximum flows were utilized.

IV. Results and Analysis

4.1 Summary of Analysis Method

Using models derived from JEFX 06 scenarios, architecture products and mappings, the network structures of the Process, People, and Application-Systems layer were analyzed and N_{layer} for each was quantified. Results for each layer are presented individually. The NC score was also determined for the baseline model. To show how characteristics change with a change in network structure, the Application-System layer network was changed by removing one edge at a time. Each iteration of this dynamic analysis simulated the loss of communication between two applications or systems. Using the comprehensive interlayer mapping, the dynamic effects of those changes were propagated through the People and Process layers. This propagation simulates the ability for a commander to observe how failure of a communications link affects their people and process. Each corresponding layer's network characteristics were analyzed, quantified, and then compared to the baseline model. Finally, the mission effectiveness of the baseline and altered model are compared.

4.2 Results of the Baseline JEFX Model

4.2.1 Process Layer

The layers and relationships in the JEFX NCO model were derived from the Operational Thread Report for three operational threads: Enhance C2 SA with NTISR, Prosecute NTISR, and Prosecute TST. Figure 13 depicts the threads as three processes with successive tasks. The participating nodes and edges of the lower layers were chosen since they supported these three threads. By including only the participative nodes and edges, each network was scoped to a manageable size.

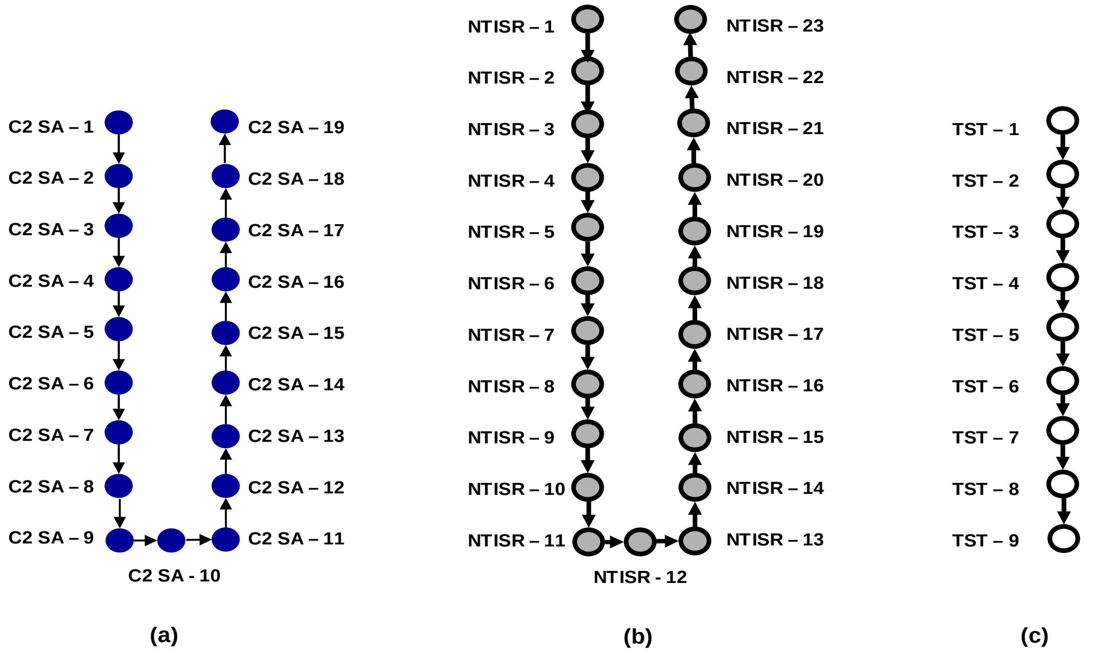


Figure 13: Process Layer based on (a) Enhance C2 SA with NTISR, (b) Prosecute NTISR, and (c) Prosecute TST operational threads.

As discussed in Section 3.4 Analysis Using the NCO Model, the metrics can yield insights into the individual node and edge characteristics. While this is not a focus of this research, the metric Edge Betweenness Centrality, can be used to illustrate the value of observations provided by investigating individual nodes or edges. The network data for Edge Betweenness Centrality of the Process layer using the C2 SA operational thread is pictorially depicted in Figure 14. This figure reveals that two edges are very central to the traffic flow of the network. The edges between C2 SA-9, C2 SA-10, and C2 SA-11, are part of the shortest path between any two tasks supporting the C2 SA operational thread. These two edges are the most crucial transitions for this process. Theoretically, the completion of all the C2 SA tasks relies on these two edges most heavily.

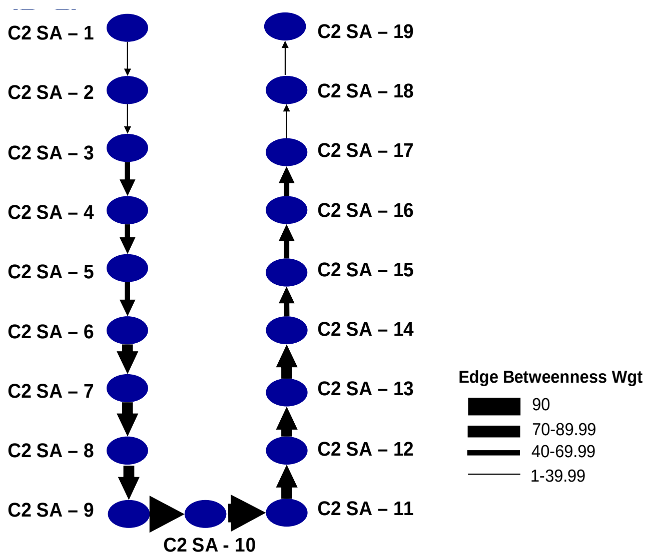


Figure 14: Edge Betweenness of the C2 SA Operational Thread.

The network characteristics of the Process layer, using the C2 SA operational thread was compiled into a single network score. The network characteristics for the Process layer using the Enhance C2 SA operational thread is shown in Figure 15. Based upon these results, the N_{layer} (Process) value is 12.46. As a measure for the baseline Process layer, this score would be used to evaluate the how changes affect the network.

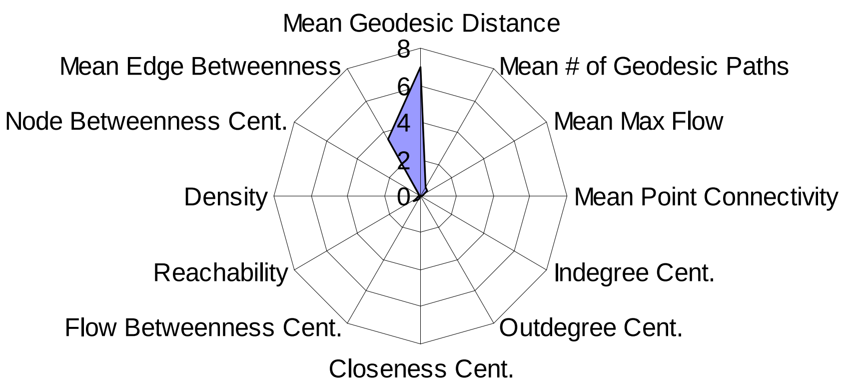


Figure 15: Network Characteristics of the Process Layer Using C2 SA Operational Thread, with N_{layer} (Process) = 12.46.

Due to the similarity in network structure, the Prosecute NTISR and Prosecute TST threads would yield similar results and can be found in Appendix A.

4.2.2 People Layer

The network in the People layer was extracted from the JEFX Operational Thread Reports and OV-5 Activity Model, scoped for three operational threads: Enhance C2 SA with NTISR, Prosecute NTISR, and Prosecute TST. The resultant graph of the network is shown in Figure 16.

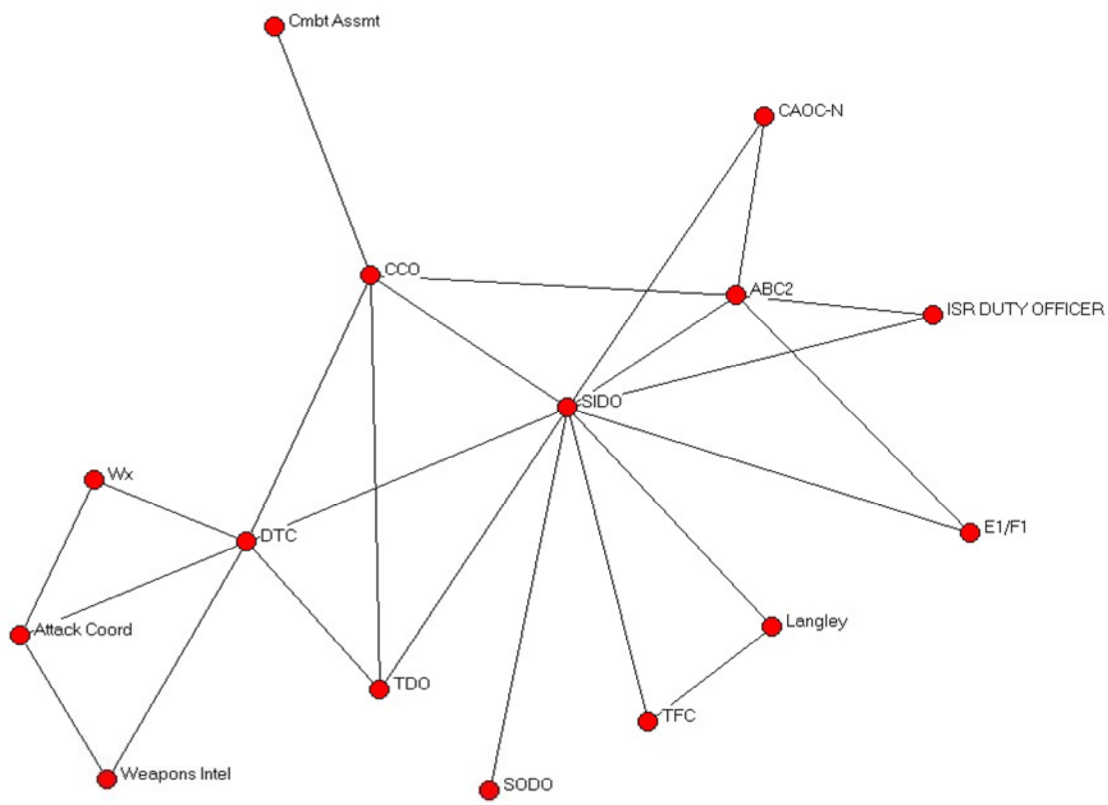


Figure 16: People Layer derived from Prosecute TST, Enhance C2 SA, and NTISR Operational Threads.

Again, from an individual node or edge perspective, the Edge Betweenness Centrality data of the People layer is pictorially depicted in Figure 17. In this network, the edge between the SIDO and DTC is the most central edge, occurring on the most number of shortest paths between nodes. Thus, the relationship between the SIDO and DTC is very crucial in supporting the most efficient social network among all the players of this layer. Should this relationship disappear, perhaps due to personnel changes at the DTC, the Edge Betweenness Centrality data would be altered. The network would most likely become less efficient because the SIDO-DTC edge was a favored "short-cut" in the baseline network structure. Therefore, a commander may value this relationship and try to ensure that the SIDO and DTC are always trained to maintain an active working relationship.

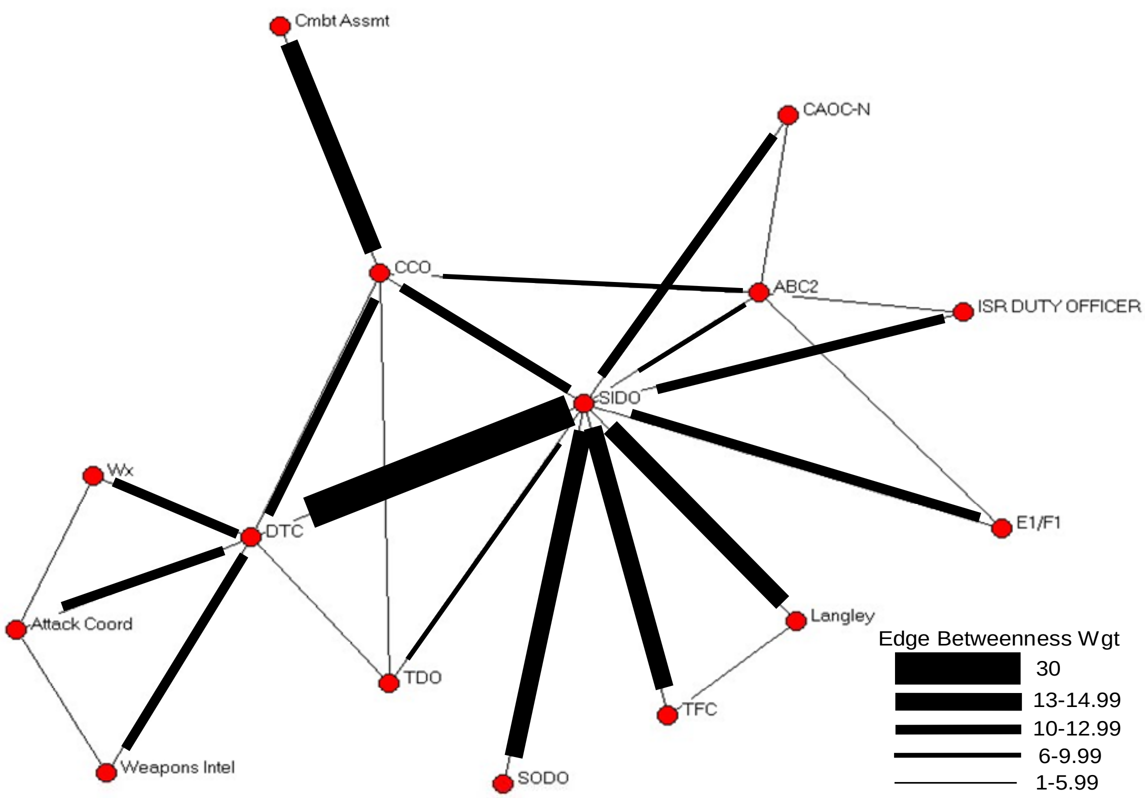


Figure 17: Edge Betweenness of the People Layer.

The network characteristics of the People layer was compiled into a single network score. The network characteristics for this structure are shown in Figure 18. Based upon these results, the N_{layer} (People) value is 12.96. As a measure for the baseline

People layer, this score would be used to evaluate the how structural changes affect the network.

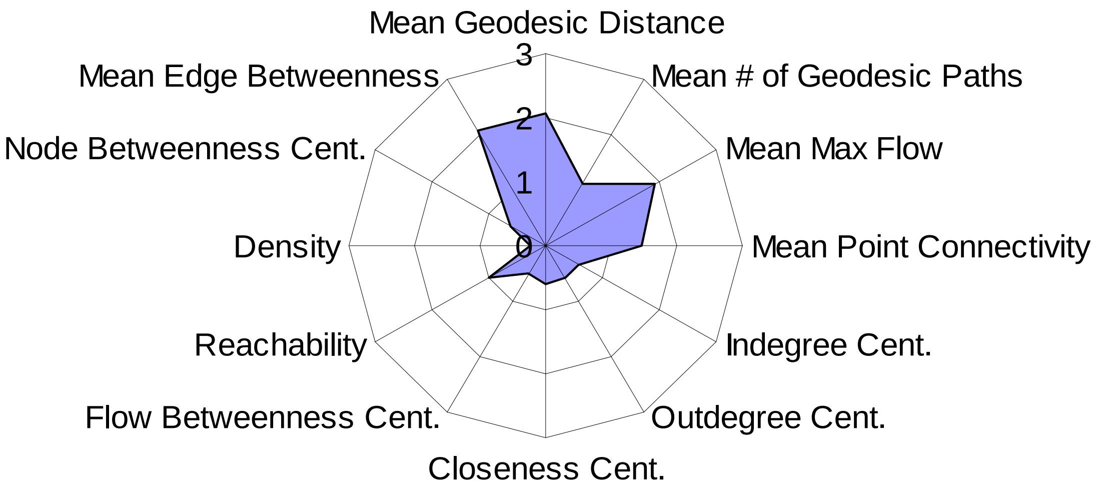


Figure 18: People Layer Network Characteristics, with N_{layer} (People) = 12.69.

4.2.3 Application-System Layer

The Application/System layer was derived from the JEFX Operational Thread Reports, SV-1 System Interface Diagram and SV-4 Data Flow Diagrams, filtered for the applications and systems that support the three operational threads: Prosecute TST, Enhance C2 SA with NTISR, and Prosecute NTISR. The resultant graph of the network is shown in Figure 19.

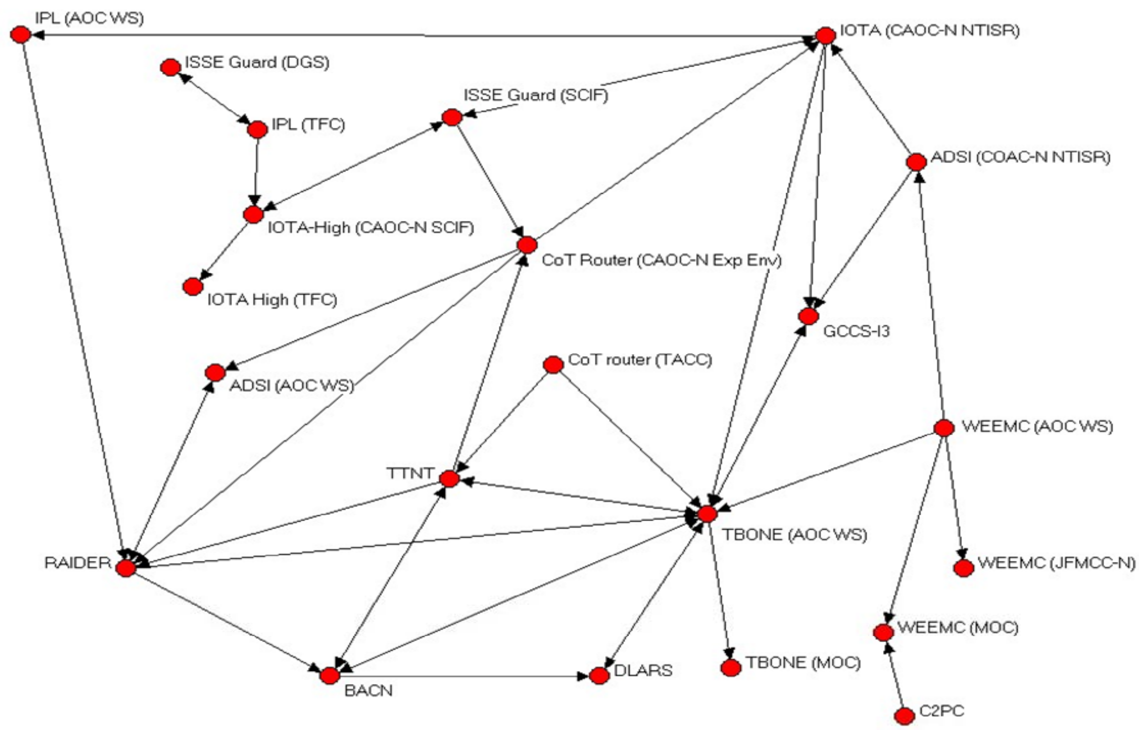


Figure 19: Application-System Layer Derived from Prosecute TST, Enhance C2 SA, and NTISR Operational Threads.

From an individual node or edge perspective, the Edge Betweenness Centrality data of the Application-System layer is pictorially depicted in Figure 20. In this network, the edges between the TTNT system, CoT Router, and the IOTA in the CAOC are the most central, occurring on the most number of shortest paths between nodes. The edges at this layer are represents data-centric interoperability between the systems, i.e., two systems may not be completely interoperable, but interoperability for specific data elements has been established. Thus, these most central edges can be seen as very crucial data transfer links within this network. These links may warrant special maintenance to ensure lower outage rates. Conversely, lower Edge Betweenness Centrality scores may suggest areas for improvements to increase interoperability between applications and systems.

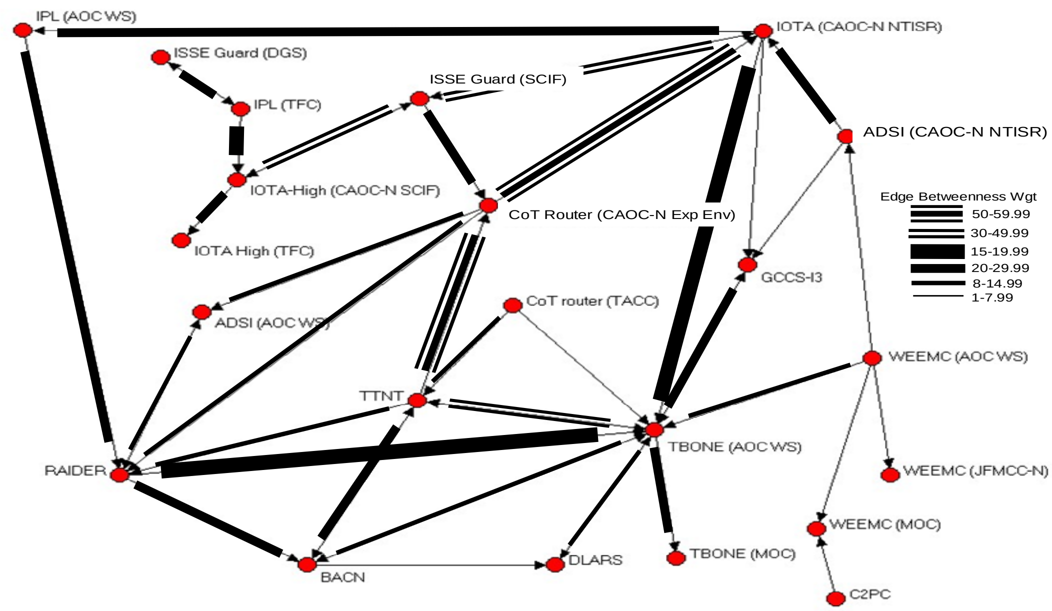


Figure 20: Edge Betweenness of the Application-System Layer.

The network characteristics of the Application-System layer were compiled into a single network score. The network characteristics are shown in Figure 21. Based upon these results, the N_{layer} (Application-System) value is 7.79. As a measure for the baseline Application-System layer, this score would be used to evaluate the how changes affect the network.

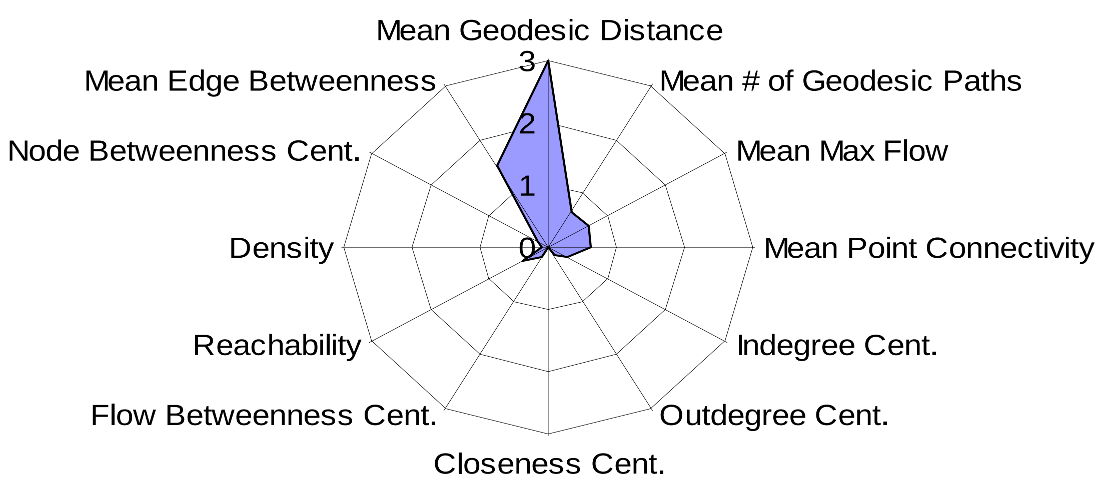


Figure 21: Application-System Layer Network Characteristics, with N_{layer}(Application-System) = 7.79.

4.2.4 Network Centricity of the Baseline JEFX Model

The NC score of the baseline JEFX model for the Enhance C2 SA scenario is N_{layer} (Process) * N_{layer} (People) * N_{layer} (Application-System) = 12.46*12.69*7.79 = 1231.7. Again, this score would be used to evaluate the how changes to any supporting networks affect overall network centricity.

4.3 Demonstrating Multi-layer traceability through Dynamic Analysis

When studying networks, it is important to understand the network's characteristics, not only structurally, but dynamically one. How does the network behave as changes occur? Determining the effectiveness of a command and control network resides in understanding the characteristics of the baseline network and then understanding how excursions affect that baseline network. The commander wants to know more than the fact that a server or router is out of service, he/she wants to know how that outage will affect his people and ultimately the mission.

The layered model of NCW was proposed to account for the many different types of networks that contribute to network centric operations. Using the model, derived JEFX networks, and the appropriate mapping between network layers, the effects of changes at any level can be traced through each layer. Figure 22 illustrates the mapping and traceability of edges through all the layers of the model.

The analysis uses three layers to demonstrate the network layer interactions: the System-Application Layer, the People Layer, and the Process Layer. The objective was to quantify the dynamic change in network characteristics of each layer as edges were iteratively removed from the lowest layer. This removal scheme simulated the outage of

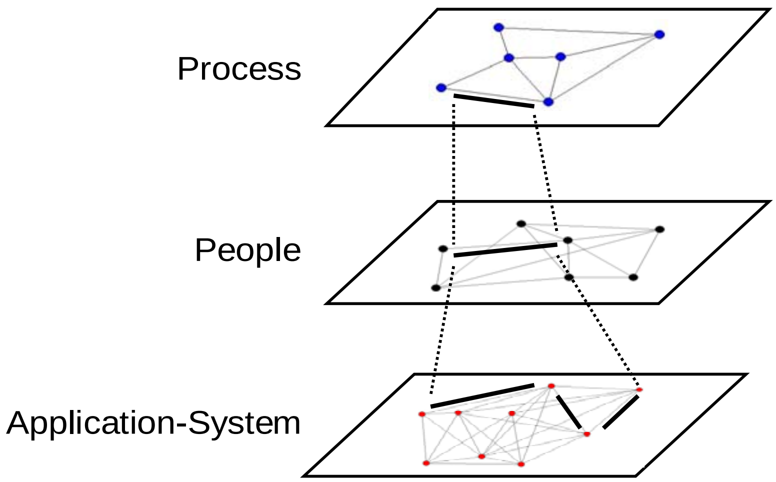


Figure 22: Mapping of Edges Between Layers Allows Effects Traceability Up and Down Through All Layers of the Model.

communications between two systems or applications. Therefore, each edge removal was considered one excursion from the baseline. As each edge was removed, the comprehensive edge mapping matrix was used to determine the edges from other layers that would be affected by each edge removal. The effected edges were also removed and the resultant network was re-measured to determine its new network characteristics. These new characteristics were compared to the baseline and the difference was recorded. From these results, the impact of each edge removal and the average could be observed. Since the Application-System layer had 34 edges to remove, 34 excursions were analyzed.

The labeling convention of the graphs requires some explanation. Each edge in a network was arbitrarily given an edge number. For instance, A-S-1 refers to the “edge 1 in the Application-System Layer.” If the removal of an A-S edge resulted in a change in the People or Process layer, that constituted an excursion from the baseline network. Each excursion was named after the A-S edge that caused it. Therefore, for example, on the People layer graphs, the data for excursion A-S-16, 25 means that "the resultant data occurred with the removal of A-S-16, and, on separate occasion, occurred again with the removal of A-S-25." Thus, the removal of either A-S-16 or A-S-25 at the Application-System layer resulted in the same impact to the People layer above it.

The removal of the Application-System layer edges changed the characteristics of the People layer, as shown in Figure 23.

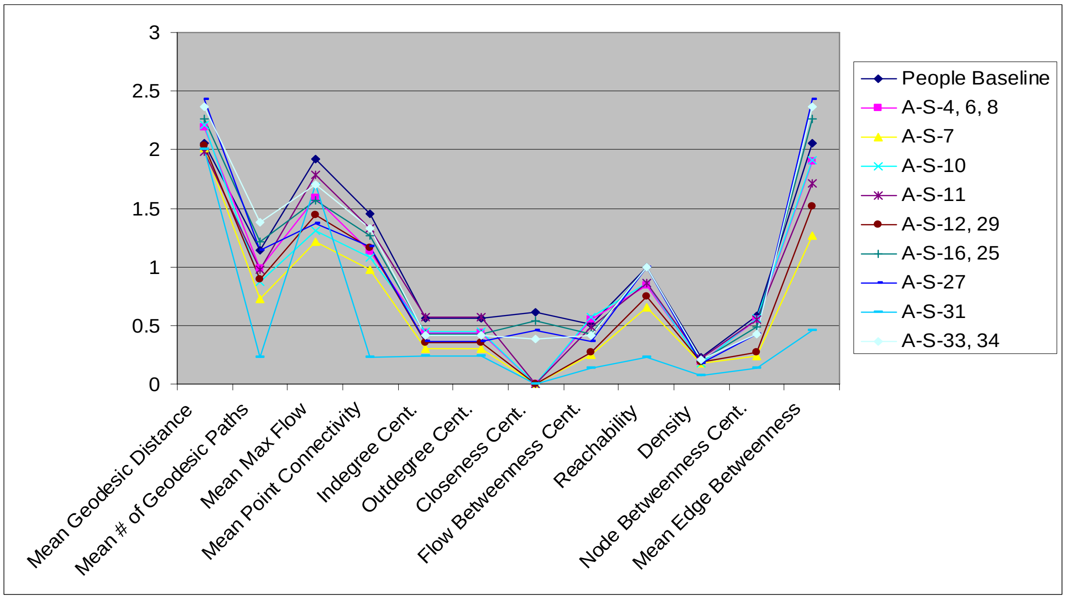


Figure 23: Resultant Network Characteristics of the People Layer as Dynamic Changes Occur at the Application-System Layer.

As a representative discussion, the excursion A-S-27 will be analyzed. Specific to this excursion, the removal of A-S-27, the edge between the "WEEMC (AOC)" node and the "ADSI" node, at the Application-System layer mapped to the loss of edges at the People layer between "Weather-DTC," "DTC-TDO," "DTC-SIDO," "SIDO-CAOC-N node," and "SIDO-ISR Duty Officer" nodes.

The baseline People layer network had a Mean Geodesic Distance of 2.057. With the removal of A-S-27, the resultant Mean Geodesic Distance increased to 2.429. For network centric operations, this increase may imply that key persons who helped to connect other persons together have been removed--vital relationships have been severed. Thus the measure of geodesic distance in a network contributes to the NCO-CF measures of shareability and collaboration. An increase in geodesic distance inherently affects a person's ability to influence or collaborate with others. In the context of reach, as one person relays a message to another, who in turn relays that message to yet another person, that message will experience some type of attenuation, distortion in meaning or level of influence. Hence, from a NCW perspective, one may desire a shorter average distance across nodes in network to ensure the integrity of communications between persons. In other words, one may want to ensure that those involved in a certain mission have a close working relationship with everyone on that mission, rather than relying on intermediary relationships to get the job done.

The Mean Number of Geodesic Paths for this remained unchanged, standing at 1.14. From a networking perspective, this metric contributes to the measure of robustness in the form of redundancy in the network, since the number of possible paths between person-to-person still remains steady. Though the geodesic distance has increased, the means of maintaining the relationship has not. Hence, for this excursion, the JEFX People network could be considered to have an acceptable level redundancy, enough people had forged working relationships to ensure the ability to reach any two persons stayed the same.

The baseline Mean Maximum Flow was measured at 1.92. For excursion A-S-27, this metric value decreased to 1.37. For the People layer, this decrease would indicate that the relative capacity collaborative influence is lower in this excursion. This result would be expected since the overall number of edges in this excursion, where influence and collaboration could have flowed, has been removed.

Mean Point Connectivity is the average number of nodes that must be removed to completely disconnect two nodes from each other. The baseline network measured at 1.46 and the excursion measured at 1.17. This decrease in point connectivity indicates an increase in overall relationship vulnerability since there are fewer persons connecting two specific persons. Should those connecting persons be removed, isolation may result. The more vulnerable a person is to isolation, the more difficult it is to maintain a network centricity at any level. Hence, point connectivity is an NCO measure of a network's vulnerability.

Both the In-Degree and Out-Degree Centrality of the baseline network is 0.51; the excursion measures at 0.37. In-Degree and Out-Degree Centrality at the People layer represents the relative number of connections each person has to the persons adjacent to him or her. With the decrease in the number of edges in this excursion, this decrease is expected. If the In-Degree and Out-Degree are put in the context of node utilization, how over-worked or under-utilized a person may be (as defined in Section 3.6.1), any decrease from a healthy baseline value would indicate that the network could be more used more efficiently.

Closeness Centrality for the baseline People network is 0.61. The excursion network is 0.46. This metric measures the relative ability for a node to access all other nodes based on that node's distance from all other nodes. For a network, the higher the Closeness Centrality, the closer a node is likely to be to its neighbors. From a NCO perspective, this measure, at the People layer, would be an indication of the cohesiveness of the working relationships. Greater cohesiveness should contribute to better collaboration and information sharing environments. With the removal of edges between persons and the increase in mean geodesic distance, it is expected that the Closeness Centrality should decrease for this excursion.

Flow Betweenness Centrality measures how much flow could pass through each node from a network-wide perspective. The baseline measure is 0.5; the excursion case measured at 0.36. This decrease is because several of the removed edges prevented several nodes from contributing to the flow of the network, even though they remained as nodes in the network. These noncontributing nodes had a degree of 1. From a NCO perspective, such a decrease may indicate nodes that are, in essence, "dead ends". A node in a "dead end" position is vulnerable because it only has one connection to the rest of the network. Lower Flow Betweenness Centrality could also indicate inefficiency in the network, since potential flow paths are not being instantiated.

Reachability is a straightforward indicator whether one node has any path to another node. Since there are no isolated nodes in the baseline or excursion case, both have reachability scores of 1.0. There is some path, long or short, that connects each person at the People layer to another. If isolated nodes occurred in an excursion, the score would be less than 1.0.

Density is an indicator of how strongly a network is connected, based upon the number of nodes in the network, how many possible edges could exist and how many edges actually do exist. The baseline People network has a density of 0.23 and the excursion has a measure of 0.181. A decrease is expected due to the removal of edges while keeping the same number of nodes in the excursion. However, the true value of this measure is that it serves to indicate the edge saturation of a network. A heavily saturated network of People may be good from a collaboration standpoint--if each person had a one-to-one working relationship with everyone else, collaboration may be more easily achieved. There would be less second-hand news. However, depending on the network layer under consideration, complete saturation may be very inefficient. A Physical Infrastructure Layer with a density of 1 may be extremely expensive to maintain. A nominal density may be a better solution for that case.

The Node Betweenness Centrality measures the betweenness of each node relative to the entire network-wide. The baseline case measured at 0.59 and the excursion measured at 0.43. As discussed earlier with the decrease in Flow Betweenness Centrality, the decrease in Node Betweenness Centrality is also due to the introduction of "dead end" nodes in the excursion. These "dead end" nodes do not lie between any two nodes, thus contributing to the decrease in overall network betweenness.

The Mean Edge Betweenness of the baseline People Layer is 2.06. The excursion's mean is 2.43. The increase is expected since the excursion decreased the number of edges, but kept the number of nodes the same. The number of geodesic paths traversing each edge between two nodes must increase since there are less path choices to cover an equal number of nodes. This measure reflects the criticality of an edge. From a NCO perspective, if many paths traverse a certain edge, that edge may require more protection because it is a much used relationship. For the People Layer, a high edge betweenness between two nodes indicates high collaboration. For a lower layer, it may indicate a critical communications link or a link that needs to have its load dispersed among other paths.

For the A-S-27 excursion, the N_{layer} (Process) = 8.03, N_{layer} (People) = 11.71, and N_{layer} (Application-System) = 8.64. The NC score of the baseline JEFX model for the Enhance C2 SA scenario is N_{layer} (Process) * N_{layer} (People) * N_{layer} (Application-System) = 8.03*11.71*8.64 = 812.43. The NC score for the A-S-27 excursion is lower than the baseline JEFX model NC score of 1231.7, a 34% reduction.

In Figure 24, the network characteristics from all 34 excursions were averaged and compared to the baseline data to determine the change of the excursion network characteristics to the baseline network characteristics.

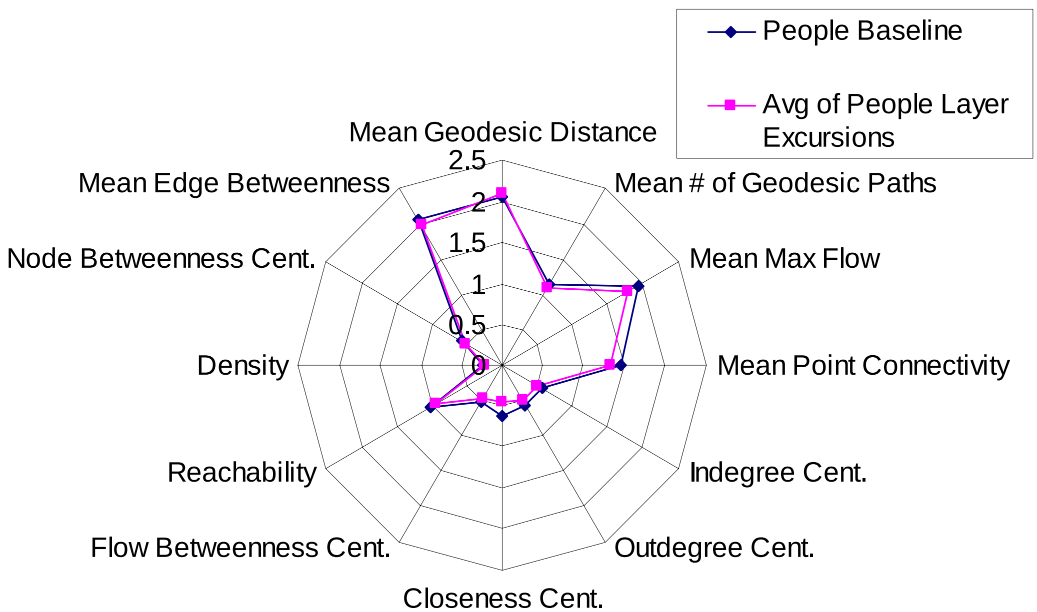


Figure 24: Average Change in People Layer Network Characteristics as Compared to the Baseline, Resulting in an N_{layer} Decrease of 6.69% Across All Excursions.

This plot reveals that, on the average, any degradation from the Application-System layer causes degradation at the People layer.

Assuming that the baseline People layer is the preferred network, these observations may be used to design the People layer so that any perturbations of the underlying Application-System layer results in minimal changes in the characteristics of the People layer. The various excursions also highlight the boundaries of how the People layer will change. These boundaries are helpful in the areas of experimentation and design.

Recall that the edges at the People network represent the working relationship between two people. If the baseline network shows two persons working with each other and an excursion removes that edge, does that removal indicate that those two persons have suddenly suffered amnesia and no longer know of each other? No, from a practical sense, each excursion at the People layer is a departure from the ideal set of relationships, which is represented by the baseline People network. The reader should interpret each People layer excursion as the representative people network if those persons never knew of each other. From this perspective, one can socially design the working relationships that may best serve a mission objective and, use excursions to measure the effects of not having the ideal relationships established.

The above discussion has been a network-focused view of how the metrics can be applied at the People layer. However, each contributing node in the network also has associated characteristics that contribute to the network-level metric. For the People layer, for example, the node level data is very useful to pinpoint the behavior and effects of a particular person of interest.

The discussion also showed how, using the multi-layer model of NCO and the mapping concept, the effects of a change at one layer, in this case the Application-System layer, results in observable changes in network characteristics at another layer, the People layer. Hence, the changes to the network characteristics can be measured and analyzed for their impact to network centric operations.

This analysis continues through all layers of the model. The results show the effect of the same set of Application-System layer excursion on the upper-most layer of the NCO model, the Process layer. Data has been collected for each of the chosen JEFX process threads, C2 SA, Prosecute TST, and Non-Traditional ISR. Similar to the discussion of the People layer, each process thread has three data charts associated with it.

Like the People Layer, the data showed the general trend of a degradation of each Process when Application-System edges were removed. This makes practical sense. If a Process is dependant upon People who, in turn depend on Applications and Systems, the degradation of communications at the lowest layer will hinder People from doing their tasks. If tasks are not completed, the Process cannot be completed. Because of the linearity of the given JEFX Processes, any degradation at the People layer would affect the Process layer.

The Figures 25 represent the results for the Process layer for C2 SA operational thread. The general trend of the data indicated a decrease in N_{layer} for each excursion when compared to the baseline.

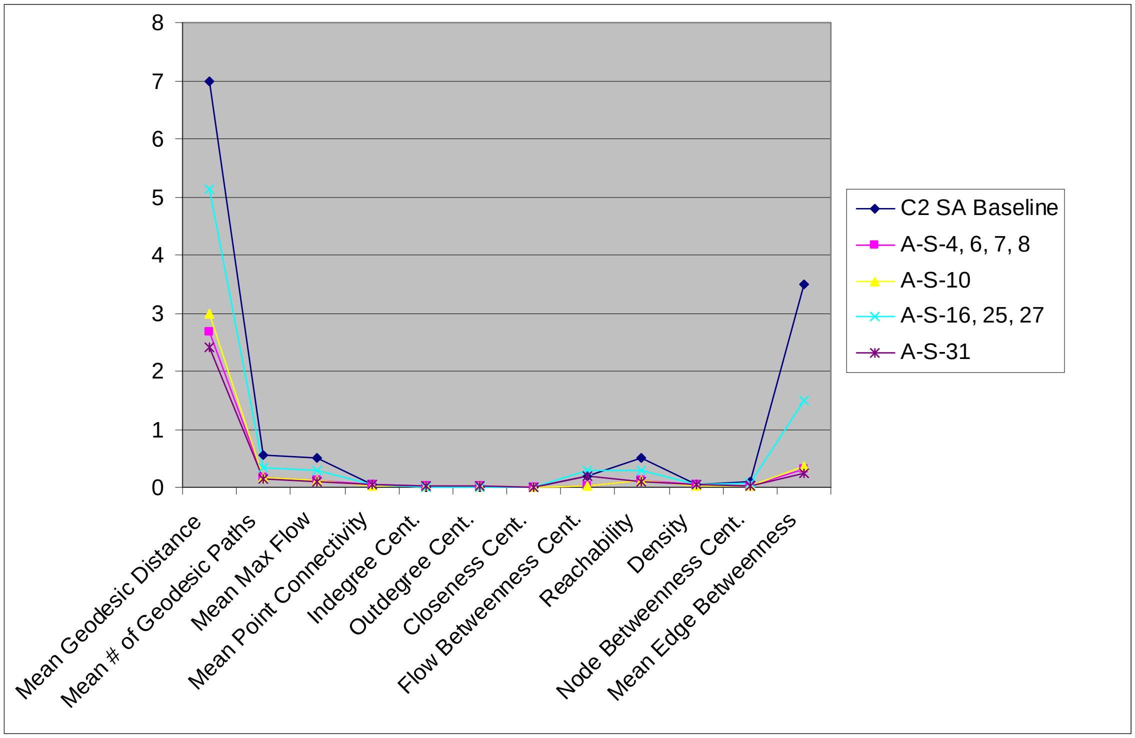


Figure 25: Resultant Network Characteristics of the Process Layer, using the C2 SA Operational Thread, as Dynamic Changes Occur at the Application-System Layer.

In Figure 26, the network characteristics from each excursion were compared to the Process layer baseline network characteristics. The average of all the deltas was then plotted against the baseline. This plot reveals that, on the average, any degradation from the Application-System layer causes also causes degradation at the Process layer.

Due to the similarity in network structure, the NTISR and Prosecute TST threads would yield similar results and those results can be found in Appendix A.

The each operational thread was modeled as a directed graph. As a result, the variability of the In-degree and Out-Degree Centrality is very low in each of the Process layer threads because the graph is a rather simplistic, linear one. Because these graphs are unconnected, and therefore, contains infinite distances, the Closeness Centrality value for both the baseline and excursions, could not be calculated and has been entered as a 0.

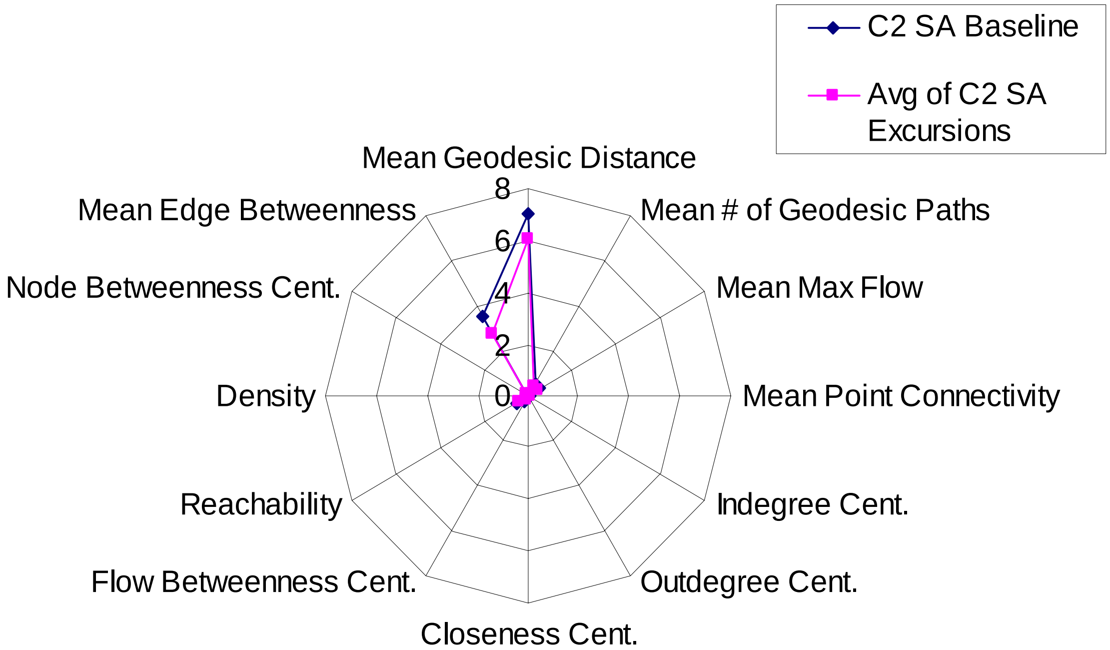


Figure 26: Average Change in C2 SA Process Layer Network Characteristics as Compared to the Baseline, Resulting in an N_{layer} Decrease of 15.68% Across All Excursions.

The mapping matrix can also be used to determine the tasks that were incomplete due to the removal of a certain Application-System layer edge. Likewise the matrix also shows the persons at the People layer responsible for the completion of a task. Using this traceability, a commander can follow the effects of an Application-System degradation, through the effect on the People layer, up to the ultimate effects at the Process layer. For example, the traceability for the A-S-27 chain would read as follows:

1. Degradation at the Application-System Layer: results in the removal of edge A-S-27 (loss of interoperability between "ADSI" and the "WEEMC" node)
2. Degradation at the People Layer: Removal of edges between the following node pairs "Weather-DTC," "DTC-TDO," "DTC-SIDO," "SIDO-CAOC-N node," and "SIDO-ISR Duty Officer."

The commander can use this data to apply improvements to TTPs, changes to organizational structure, or upgrades to applications or systems. These changes can be justified more easily because mission impacts can be connected to each requirement. In addition, once the changes are instantiated, the commander can quantify the level of improvement that results.

4.4 Measuring Mission Effectiveness

Recall that the proposed degree of mission effectiveness is sum of the ratio of tasks and edges completed. The mission effectiveness of A-S 27 excursion for the C2 SA operational thread is measured at 1.89. This result is based on the C2 SA thread having 19 of 19 completed tasks and 16 of 18 completed transitions. The baseline mission effectiveness measure is 2.0, since all tasks and transitions were completed. Therefore, the loss of the communications link between the ADSI and the WEEMC caused 0.2 degradation of the C2 SA process, equating to a 10% decrease in mission effectiveness.

V. Conclusion and Recommendations

5.1 Research Contributions and Implications

This research aimed to meet two objectives. The first objective was to extend the NCO-CF by proposing metrics that would allow a more objective way to quantify network centricity. While the NCO-CF does quantify complex, net-centric factors, the subjective nature of several metrics do not necessarily allow for the repeatable, analytical results usually required for venues such as experimentation and design. In addition, for DoD to improve the network centricity of various environments, one needs to understand the how network structure bounds the possibilities of improvement. This research demonstrated the importance of baselining network characteristics at all levels (individual, by layer, and holistically) and the changes to those characteristics when the network structure changes.

The metrics, such as Flow Betweenness Centrality and Density, were chosen based upon applicability to several NCO-CF attributes. These graph-theory-based metrics have a network-wide focus. Additional metrics, such as N_{layer} and the NC score provide a method for assigning holistic measures for the NCO.

The second objective was to show how the mission effectiveness of command and control can be determined through network analysis. The multi-layer model of NCO was used to demonstrate that the effects of lower lever network changes can be traced and measured at higher levels. Ultimately, at the top-most layer, the Process layer, mission effectiveness can be quantified. Through the comprehensive mappings between layers, a commander can easily determine how a communication equipment failure will affect the processes he needs accomplished, which reflects his mission effectiveness.

The multi-layer model of NCO was introduced and used for both objectives. As the model suggests, the success of NCO relies of several layers of networks, all which depend on each other and ultimately culminate at the Process layer with the accomplishment of some process. The model accounts for the pillars of the net centric forces outlined in Joint Doctrine and other guiding literature.

5.2 Recommendations for Action

As stated in JV2020, an underlying foundation to the net-centric force is information. That information must reach the "edge organization" and "edge user" as defined in "Power to the Edge." To do so, NCW relies heavily on people for collaboration and self-synchronization, and for interoperability between applications and systems. People must foster relationships with each other to enable collaboration and self-synchronization. They can more successfully complete processes to achieve mission effectiveness.

One recommendation for action is to extend the Network Centric Operations Common Framework Version 2 (draft). The practice of using graph-theoretical metrics (and, perhaps, the proposed N_{layer}, NC, and mission effectiveness measures) and a layered model of NCO with which to study networks should be adopted into the NCO-CF. Such metrics provide insight into the structures and dynamic behavior of networks. With regard to centrality metrics, they also yield information regarding the relationship of each node to other nodes in the entire network, not just the direct neighbors. Without such practices, evaluations of network centricity will remain incomplete.

A second recommendation for action is to augment current DoDAF architectural products with mapping products connecting not only systems to operational nodes, but to the people using them. Currently architecture products connect information to operational nodes (OV-3, Operational Information Exchange Matrix), operational nodes to systems (SV-5, Operational Activity to Systems Function Traceability Matrix) and information to systems (SV-6, Systems Data Exchange Matrix). However, there is no product that includes the equivalent of the People layer mappings, nor is there an equivalent of a comprehensive mapping. This research has shown that the comprehensive mapping methodology is useful for allowing a commander to trace perturbations in people, system, application, etc. failure to a mission/process impact. Including such a product would provide traceability between all the architecture elements.

5.3 Recommendations for Future Research

One area for future research is to create higher fidelity models of networks and validate the results with operational data. Though JEFX architecture was used to originally construct the networks, the extent of the required data was not among the planned documentation products of the JEFX community. For example, the relationships of the Applications and Systems would have been more complete if data from the OV-2 (Operational Node Connectivity Description), OV-3 (Operational Information Exchange Matrix), SV-5 (Operational Activity to Systems Function Traceability Matrix), SV-6 (Systems Data Exchange Matrix). The availability of an OV-4 (Organizational Diagram) would greatly have facilitated the modeling of the People layer. Earlier coordination with the JEFX communication would allow the model to be improved and also facilitate inclusion in the data collection plans. These steps would allow analytical data to be validated against results from live-fly scenarios.

Another area of future research is to investigate other layered relationships between NCO elements. The multi-layer model presented here is a two dimensional one, layers travel up and down. However, a more sophisticated "layering" scheme may yield additional insights. One such layering scheme would be placing the Applications Layer at the same level at the People layer, so there is triangular relationship between Process, Applications, and People layers, in other works, a graph of graphs. The System layer and Physical Network layers would remain as supporting layers to the Application layer. This configuration may better model machine-to machine functions. Lastly, the addition of a data model as another graph layer and its relationship to the other layers should also be explored. This addition would be particularly relevant to increase visibility into the effects of information flows.

5.4 Closing Comments

The DoD will continue its transformation to a network centric force for years to come. People, systems, applications, and physical infrastructure will be networked at an increasing rate and intensity. New IT concepts such as Service Oriented Architectures could usher in a new era of distributed web services. Interoperability will also improve, furthering the dependence on networking. The methods by which network centricity analysis is conducted must also evolve towards a network focus. The field of network science has been applied to studies of complex networks in areas ranging from the World Wide Web, and social networks to disease control and electrical power outages. This field must be recognized as having merit for use in studying DoD networks. With the focus on increasing collaboration, information sharing, and synchronization, more emphasis must be placed on the interrelationships between entities and the structure of the network. To again echo the words of Duncan Watts, "In a connected age, therefore, *what happens and how it happens depend on the network"* (Watts, 2003:28). The DoD is certainly entering the "connected age" and would greatly benefit from adopting Dr. Watt's point of view.

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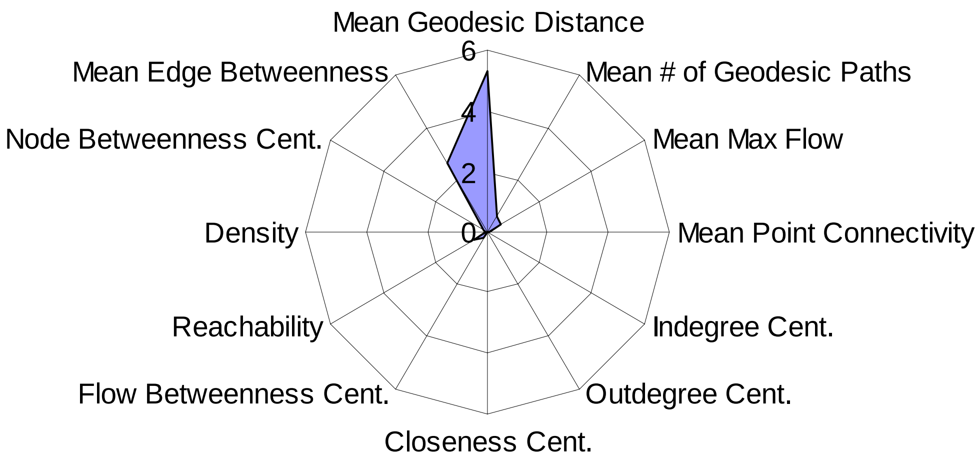
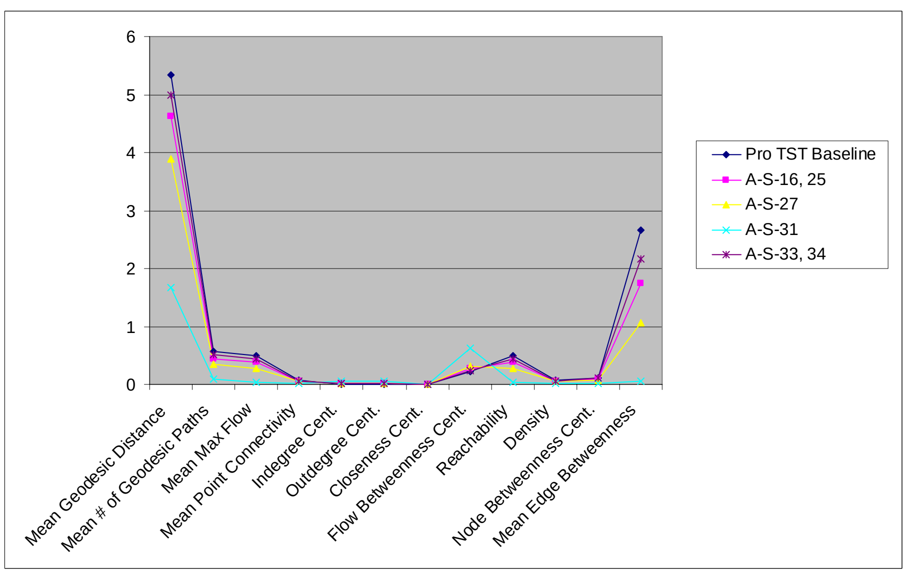
Appendix. Network Characteristics for Pro TST and NTISR Process Layers

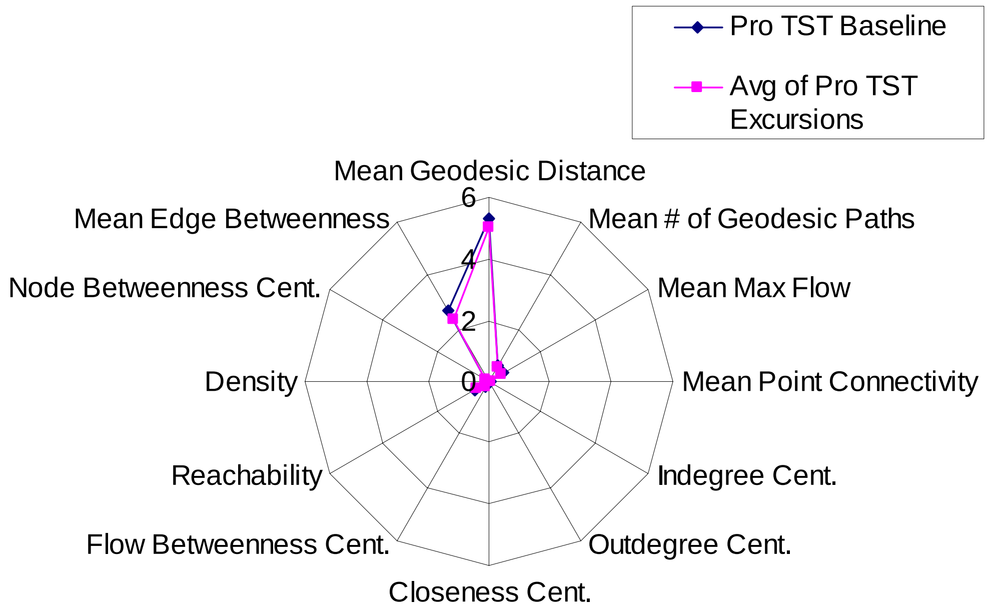
The following results are included for the Pro TST and NTISR Process Layers. The outcomes of the static and dynamic analysis were very similar to that of the C2 SA layers.



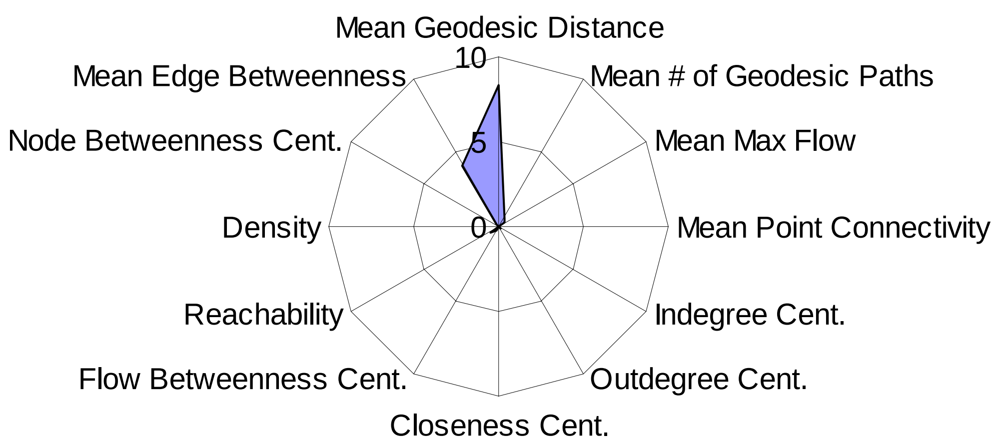
A-1: Network Characteristics of the Process Layer Using the Pro TST Operational Thread.



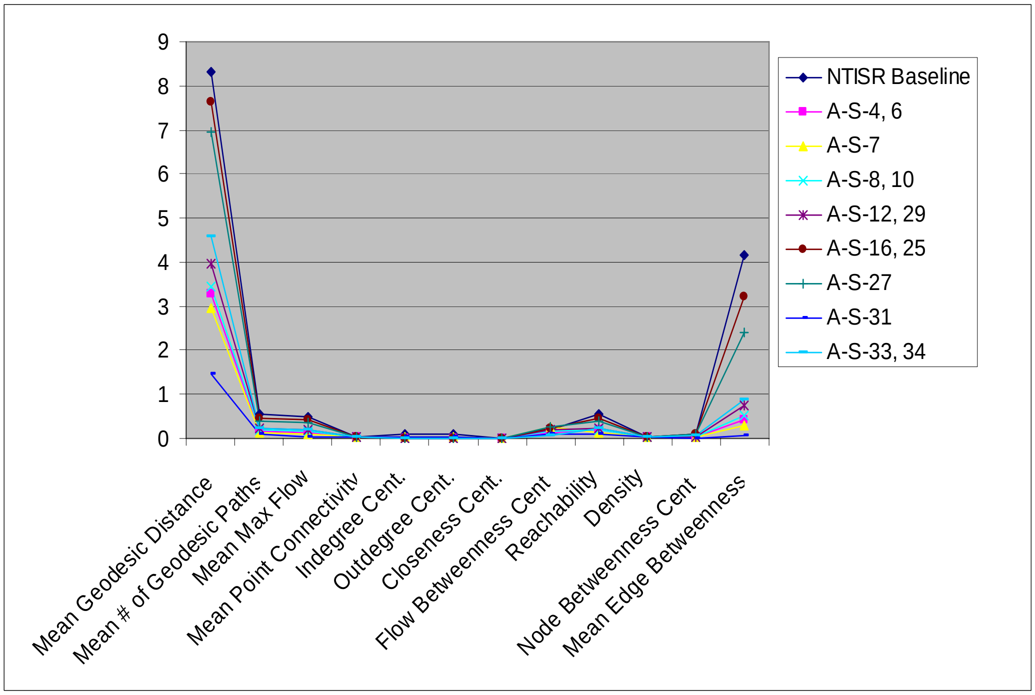
A-2: Resultant Network Characteristics of the Process Layer, using the Pro TST Operational Thread, as Dynamic Changes Occur at the Application-System Layer.



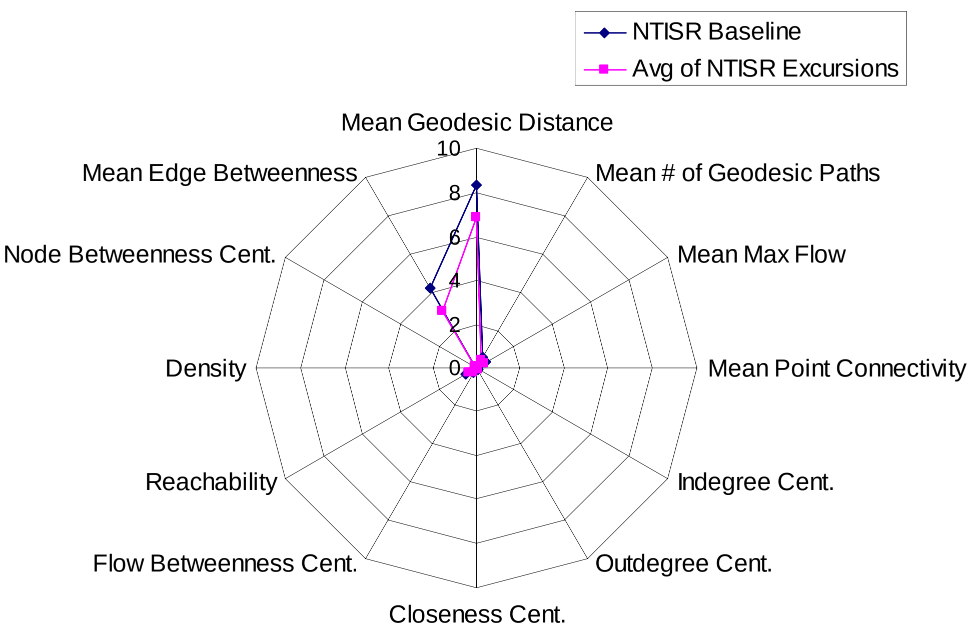
A-3: Mean Change in Pro TST Process Layer Network Characteristics as Compared to the Baseline, Resulting in an N_{layer} Decrease of 7.83% Across All Excursions.



A-4: Network Characteristics of the Process Layer Using the NTISR Operational Thread.



A-5: Resultant Network Characteristics of the Process Layer, using the NTISR Operational Thread, as Dynamic Changes Occur at the Application-System Layer.



A-6: Mean Change in NTISR Process Layer Network Characteristics as Compared to the Baseline, Resulting in an N_{layer} Decrease of 20.9% Across All Excursions.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT As the Department of Defense continues its transformations to a network centric force, evaluating DoD's progression towards net-centricity remains a challenge. This research proposes to extend the Network Centric Operation Common Framework Version 2.0 (draft) with the metrics based in graph theory and, specifically addresses, among other metrics, the measurement of a net-centric force's mission effectiveness. The research incorporates the importance of understanding network topology for evaluating an environment for net-centricity and using network characteristics to help commanders assess the effects of network changes on mission effectiveness.

The multi-layered model of Network Centric Operations and interlayer mapping are introduced to address the interdependent contributions of people, systems, and processes to the success of net-centric operations. A layered network model was populated with data derived from the 2006 Joint Expeditionary Forces Experiment (JEFX). Both static and dynamic network analyses were performed to characterize the network structures and to demonstrate how the interlayer mapping allows networks changes at one layer affects the networks characteristics of other layers. Thirty four excursions were performed on a three-layer model of JEFX network centric operations and the network characteristics were measured using twelve graph-theoretical metrics.

15. SUBJECT TERMS

Network Analysis, Command and Control, Communications Network, Network Architecture, Network Centric Warfare, Network Centric Operations, Common Framework, Metrics, Mission Effectiveness, Layered Models, Graph Theory, Edge Organizations, Edge Users, Joint Expeditionary Forces Experiment, Mapping,

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U	**U**	**U**	UU	82	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565, ext 3347; e-mail: @afit.edu

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