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THE FUTURE OF C2

An Application of Agent Based Modeling in the Analysis of Communication Links in Network Centric Operations

Topic: Modeling and Simulation

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Abstract:

Network Centric Operations is emerging as an important factor in future military applications. The tenets of NCO state that a robustly networked force improves information sharing and collaboration, which enhances the quality of information and shared situational awareness. This enables self-synchronization and improves sustainability and speed of command, which ultimately result in dramatically increased mission effectiveness[1]. Understanding how network enabled collaboration increases mission success is important. The primary reason for this experiment is to observe the effect of collaboration on task completion.

Agent based modeling fills an important analytical gap in experimentation. Such models allow for rapid, repeatable concept exploration, which is an effective means of examining the impact of network technologies on a force. The use of computer simulations provides a basis for analyzing and optimizing the abilities of military forces in NCO. In studying the use of sensor systems, shared information, and collaboration, it is possible to determine the effect of information network structures on military situations.

This work describes an investigation of the effects of collaboration on a force. The study was conducted using Map-Aware Non-uniform Automata (MANA), an agent based simulation environment. By data farming[2] relevant communication parameters such as range, capacity, latency, accuracy, and reliability across a variety of network configurations we can determine which communication factors are most important for a force to successfully share information. More specifically we will examine how a degraded communications network affects an armed force under attack. The study will explore several operationally relevant scenarios ranging from the very simple setting to the complex. Primary focus will be placed on message range and accuracy, and how each affects the unit's ability to fight and win decisively. The aim of this analysis is to gain insight on the first order effects of networking on force effectiveness.

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[1] Department of Defense. *Network Centric Warfare Report to Congress*. July 2001.

[2] Data Farming Data Farming is the method by which potentially millions of data points are explored and captured. www.projectalbert.org

Introduction

With time military organizations have changed to adapt to their circumstances and environments by developing different approaches to command and control[3]. Limited by technology and hierarchical structures, such changes result in different organizational structures. Interactions between and among members of an organization form the links in a network and define its topology[4]. An organization can be defined by the structure and nature of its of connections. An organization will function differently depending upon the relationship between its nodes, namely how many nodes are linked or not linked. An organization is comprised of multiple networks serving functions such as command, information, logistics, etc. This study focuses on the information network. The graphic below depicts four different information network topologies.

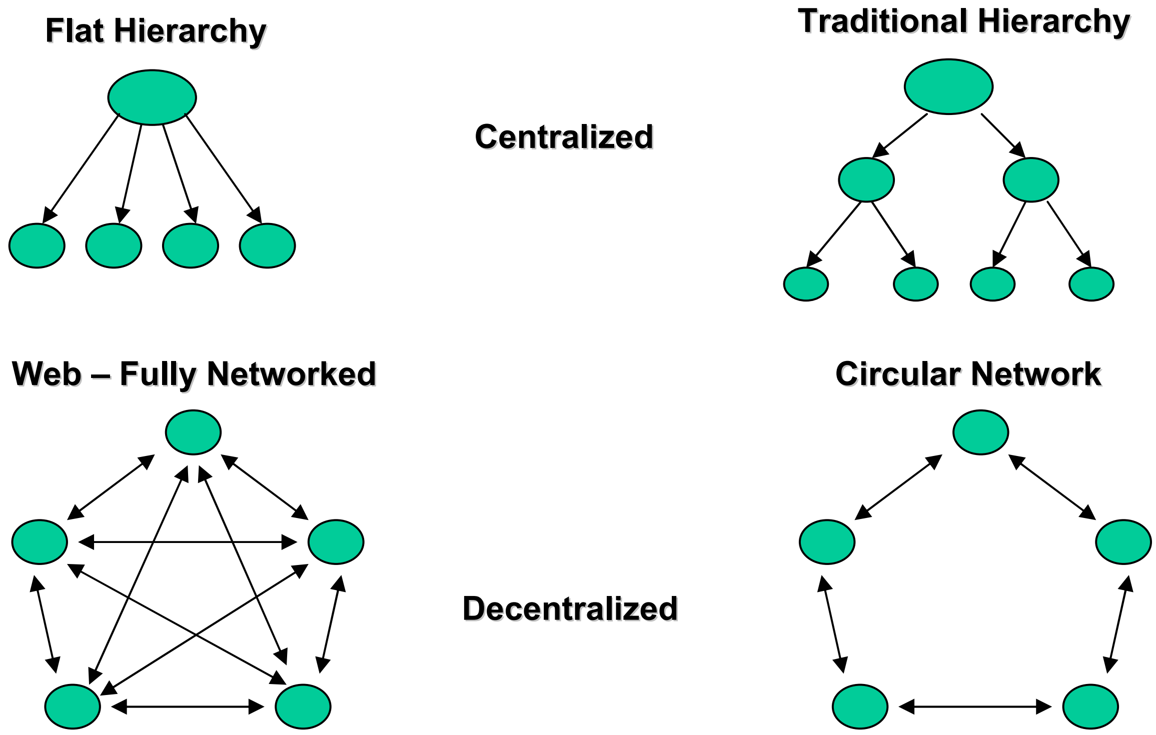

Figure 1. Four Network Topologies
Reference ***Power to the Edge***
(pg. 182)

Network nodes and communication links are illustrated by the circles and arrows. A node can function as both a sensor and a communicator. Information enters the system as each node collects organic information. Some nodes have the ability to pass that information to other nodes as directed by the links. The centralized networks, the flat and traditional hierarchies, are capable of one directional communication. In the flat topology, information is passed from a single central node to subordinate level nodes.

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[3] Alberts, David S. & Hayes, Richard E. *Power to the Edge: Command…Control… in the Information Age.* Washington, DC: CCRP Publication Series. 2003. p181.

[4] Network Centric Operations Conceptual Framework Version 2.0. 2004.

The traditional network consists of a layered hierarchy. Information is sent from a central node to mid level nodes, and then from the mid level nodes to the subordinate nodes. Unlike the communication links in the centralized networks, the decentralized networks have bidirectional communication. Nodes can collect, share, and receive information. The links in the circular network allow each node to communicate with its neighbors, while the web network is fully connected; each agent can communicate with all other agents in the network.

It is important to understand how the efficiency and effectiveness of an organization's performance is affected by the structure of its communication network. Capabilities such as information sharing and collaboration depend upon on network connections. This modeling effort was an investigation of the set of network structures illustrated in Figure 1. Conducted as part a case study for the NATO panel, Studies and Analysis Simulation of New Concepts for Command and Control (SAS-050), the goal was to explore aspects of Network Centric Operations (NCO) to support development of the group's Conceptual Model of Command and Control. A detailed exploration of the variables and relationships defined by the group aided in identifying advantages and limitations of their conceptual model. This experiment was just one method of exercising and strengthening the C2 model.

Agent based models were used to compare these network configurations. Agent based models allow users to analyze complex behaviors. These models offer the opportunity to investigate how different conditions alter the outcome of a mission. This paper explains two agent based modeling efforts, utilizing MANA (Map Aware Non-uniform Automata) developed for the New Zealand Army and Defence Force and NetLogo developed by the Center for Connected Learning and Computer-Based Modeling at Northwestern University. MANA was well suited for our network comparison modeling needs. Detailed communications for various levels of networked forces can be easily modeled using this tool, as behavior state changes can be programmed for the coordinated movement of forces. Such triggers allow a user to model agents given a set of rules over wide range of scenarios. NetLogo was useful in modeling information parsing and sharing. Unlike MANA, NetLogo is fully programmable. While the simple programming language can be lengthy, the user can construct a scenario by building capabilities that can not be found or easily demonstrated in other models. Both models are available to the public and are used by Project Albert[5]. Project Albert is an international agent based modeling community. Its members collaborate in a question based forum investigating military operations as well as operations other than war. It leverages high performance computing to allow for rapid, repeatable concept exploration. The repetition of scenario runs allows for data collection, which enables decision-makers to examine and understand the landscape of potential simulated outcomes, enhance intuition, find surprises and outliers, and identify potential options[6]. This modeling and analysis process is an effective means of examining the impact of network technologies on a force. The models are especially useful in investigating scenarios that could not feasibly be conducted in a real time experiment.

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[5] www.projectalbert.org

[6] www.projectalbert.org

One should recognize that like all models, the models used in this experiment have certain limitations. The agents in each scenario operate using their organic information and the information they are fed. The agents do not have the ability to make educated decisions by weighing risks or evaluating alternatives. Agents act based on the information they receive, in a manner dictated by trigger rules and behavior characteristics. For example, an agent with a limited sensor range of 20 on a 200,200 grid moves at a certain rate. Upon encountering the enemy with organic sensors, the agent can be triggered into a different reaction state. The agent may run away from the enemy or speed up approaching the enemy in a full on attack. In reality a soldier aware of his limited sensor range would likely approach unknown territory with caution, and upon detecting the enemy decide which plan would be most appropriate.

Modeling Efforts

Exploration of Communication Network Structures

A large portion of this work consisted of a simple comparison of four C2 information network arrangements. It was important to keep the scenarios simple in order to understand the effects of different network structures. All four communication configurations depicted in Figure 1 were modeled in a simple setting which lacked terrain and complex behaviors. All nodes in the decentralized topologies have the same capabilities. The centralized network subordinate nodes had the same capabilities as the nodes in the decentralized networks. However, the central and mid level nodes in the hierarchical structures were modeled differently. The central node was depicted as a UAV, having sensor range capabilities far superior to that of the subordinates. The UAV increases the range and quality of organic information (for the respective agent) and adds structure to the network. While each network's agent characteristics and behaviors remained stable, properties of the communication links were altered.

Each information network was modeled over a variety of mission objectives. In scenario A, agents were given the objective to get to the goal quickly at any cost. They should take the optimal path with minimal distance to traverse, minimizing the time needed to complete the mission. Agents had no consideration for losses and lacked maneuvering behaviors.

In alternative scenario B, only the traditional and web networks were modeled. Each network was modeled with and without a UAV capability. The squad agents retain their desire to reach the goal, but with minimal losses. Agents possessed maneuvering behaviors with consideration of friendly losses. The time needed to complete the mission played a lesser role in their objective.

In scenario C, two of the network structures (traditional hierarchy and the fully connected web) were modeled in a more operationally relevant setting, illustrating a United States Marine Corps Gazette Tactical Decision Game (TDG)[7]. This scenario included a complex terrain which obscured line of sight and added movement complexity. The

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[7] USMC Tactical Decision Game #97-3 March 1997.

objective in this TDG was to deplete the enemy force, establishing an initial advantage for follow on troops.

Once the scenarios were set up and tested in MANA, they were run for thousands of iterations to establish reliable data. In our run repetition, we varied the following parameters on a (200,200) grid map:

- Communications Range (100-200 grid cells, in increments of 100 cells)
- Communications Capacity (25-100 messages passed through the communications link, in increments of 25 messages)
- Communications Latency (0-15 time step delay, in increments of 5 time steps)
- Communications Accuracy (25-100% accurate passage of information for correctly detected and classified contacts, in increments of 25%)
- Communications Reliability (25-100% reliability that messages made it through the communications link, in increments of 25%)
- Red/Enemy Sensor Range (15-20 grid cells, in increments of 5 cells)[8]

By data farming these parameters we were able to demonstrate the effects of degraded communications on network structures and measure mission success. We expected our overall results to demonstrate:

- Better sharing of information leads to better performance
- Broader or earlier information sharing leads to better performance as individuals have common picture of enemy contacts before getting caught up in battle
- Full connectivity leads to better performance
- Perfect communications is preferable to degraded communications

Results

The data were explored using Avatar, a tool created by the Maui High Performance Computing Center for Project Albert. This tool allows the user to select a set of particular input values or specific MOE values to trace threads and investigate contributing factors. In each scenario we explored the data, highlighting those factors contributing to low blue (friendly) casualties and low red (enemy) casualties. An example of the output data is depicted by the graph in Figure 2. In this data plot the user has selected a set of input values or threads through the distribution. This graph traces low blue casualty results for the traditional hierarchy in Scenario A.

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[8] Note that in Scenario A runs were conducted under a variety of enemy sensor ranges. This allowed for an investigation into how blue will fair against an enemy with fewer sensor capabilities.

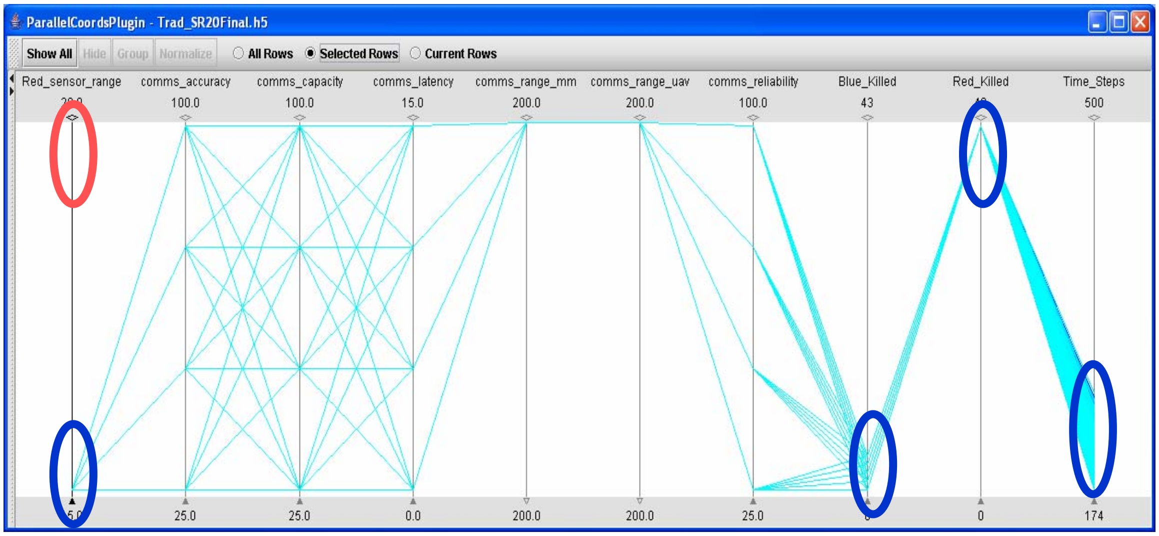

Figure 2. Parallel Coordinate Plot: Scenario A, Traditional Network, Trace of Low Blue Casualties

Scenario A

In viewing scenario A data, we observed similar results for each of the centralized information networks (traditional hierarchy and flat hierarchy) and for the two decentralized networks (circle and fully connected web).

In the centralized network data we observed that in the case when blue suffers few casualties, the amount of red killed is very high. Blue reaches the goal in a timely manner, although the time needed for the flat hierarchy to achieve the objective is more variable than the time needed by the traditional hierarchy. However it is important to note that the blue force only suffers low casualties rates when their sensor range is greater than that of the red force. These results can be observed in Figure 2.

Results for the two decentralized network topologies were even more alike. Low blue casualties were linked to a mix of high and low Red Casualties. Despite high survivability rates, the blue forces did not always achieve the mission objective. However when the blue force did reach the goal the mission was completed faster than the missions of the centralized network structures. It is interesting to note that Red sensor range was not the main indicator of success in the decentralized network topologies. The web and circle structures were less dependent on having capabilities superior to their opponent.

In summary, this scenario was a good test for comparing the flat and traditional hierarchies and the web and circle topologies respectively. Overall the centralized networks performed best due to their extra sensor range provided by the UAV[9]. It quickly became apparent that the global picture provided by the UAV gave the agents in

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[9] As stated the introduction of the UAV to a force, increases the force's capabilities. The UAV has a sensor range which covers the entire playing field. The UAV Agent is invulnerable, but it also lacks movement capabilities. It acts solely as a sensor therefore it will never reach the goal.

the centralized network a distinct advantage over the web and circle networks (as set up in the model). Therefore, the UAV capability made it impossible to directly compare the results for the two different network types.

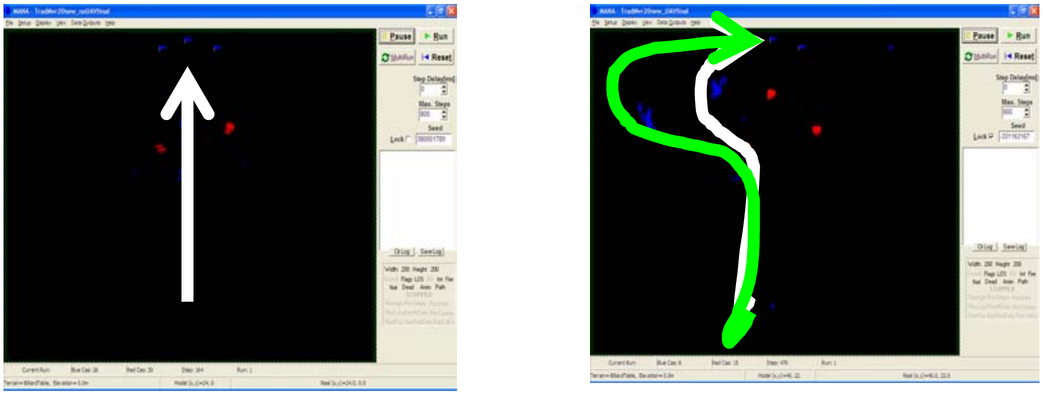
Of the two centralized networks, the flat hierarchy performed a little better than the traditional network in achieving the mission objective. In the traditional network, the mid level nodes were vulnerable to enemy fire. Further analysis indicated that once the mid level nodes were taken out, the subordinates in the traditional hierarchy had to rely solely on their organic information. The agents performed poorly without shared information.

Surprisingly, the results for the web and circle network configurations were very similar. While the circular topology statistically achieved the objective slightly quicker than the web network, the web network performed its successful missions nearly as fast and with fewer casualties. It may be the case that by introducing additional squads, namely adding more nodes, the strength of the web configuration would be more apparent.

Scenario B

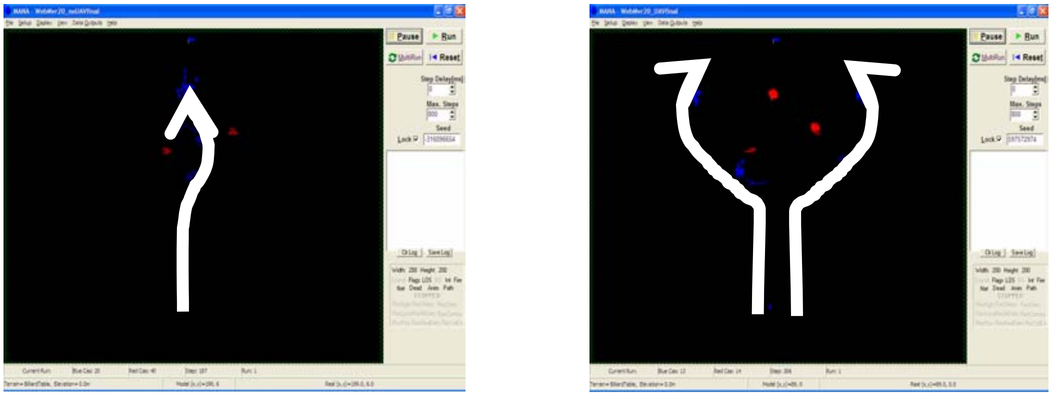
Due to similar results between the two centralized networks and the two decentralized networks in Scenario A, we chose to investigate one network from each type in greater detail. Only the traditional hierarchy and fully connected web configurations were modeled under scenario B. Each network was modeled with and without the UAV capability in order to be able to directly compare the two networks.

This scenario differs from scenario A in its initial set up. Blue agents still have a desire to reach a goal, but need to avoid casualty by maneuvering around the enemy force. The enemy is divided into three groups positioned in a triangular formation protecting the blue force objective. The effect of each network can be seen through the data collected and by viewing the squad maneuvers in playback. An illustration of the emerging maneuver patterns is depicted in Figure 3.



Traditional Network without UAV

Traditional Network with UAV



Web Network without UAV

Web Network with UAV

Figure 3. Maneuver Patterns

In the traditional configuration without UAV capability, two agents serve as the mid-level information nodes. The mid-level nodes pass their own situational information to the subordinate nodes (it has half the sensor range capability of the UAV). With a partial view of the battlefield, the blue squads head toward the goal and inherently in the direction of the enemy which corresponds to the battle space information they receive. The mid level nodes are often killed off early in the battle, severing communication lines to the subordinate agents. Lacking important information, the agents head straight up the battlefield. The agents do not have time to maneuver around the enemy. The blue agents reach the goal, but suffer great losses with more than half of their force depleted.

When the traditional communication network has UAV capability, two mid-level agents receive inorganic SA from the UAV and pass it along to their respective squad. Along with the inorganic information, the mid-level agent passes its own information. The blue squads initially have a desire to cluster, but upon enemy contact, the agents move away from red so much so that they go far out of their way to avoid the enemy. This overcompensating movement results in blue taking a long time to reach the goal. While the traditional hierarchy achieves the objective with and without the UAV, it takes more time to complete the mission with the additional sensor range. Despite the extended run time, the UAV capability added value by providing time for maneuvers and thus minimizing enemy engagements. Less enemy contact resulted in lower casualty rates.

In the web configuration without UAV capability, the blue squads quickly cluster. This desire to move toward friends kept them on a central path as they moved forward toward the goal at a quick pace. Each squad could communicate with all other squads, however each has a sensor range of only 20 (on a 200 by 200 grid). Agents were caught up in the red trap (kill sack) as their situational information covered only a small area. The squads therefore had little warning before encountering the enemy. They engaged the opposition and attempted to maneuver away from enemy fire. The blue force suffered loss, but managed to accomplish the mission in the majority of runs. It is likely that the probability of blue reaching the goal could be greatly improved with more powerful weapons. This case does a good job of illustrating the value of informed risk taking. If MANA gave the agents the ability to a weigh alternative action plans, the blue agents may have been able to avoid the trap. The ability to explore possible solutions would minimize exposing the force to risk.

When UAV capability is introduced to the web configuration, each agent has the same picture of the entire playing field. The blue squads cluster. This desire to move toward friends keeps them on a central path as they move forward toward the goal at a quick pace. Once they form one large group they tend to move away from the enemy, however by the time they organize into one collective unit, they are more than halfway across the battlefield and close to the enemy. They engage the opposition and then manage to do a good job of avoiding the enemy by splitting up, moving to the right and left of the red force. This split maneuver pattern is unique to this scenario. The mission is accomplished fairly quickly with minor losses for both blue and red. This is the optimal solution among the four test cases.

The results of this scenario were especially interesting in displaying emergent movement patterns. Additionally, the vulnerability of the hierarchical network became evident. The fully connected network proved stronger against attack.

Scenario C

The data from this scenario illustrates the effect of C2 networks on the outcome of a mission. Our team compared the traditional and web networks, with and without the UAV. With the objective of depleting the enemy force, the web topology was very successful. In fact, the web network both with and without the UAV was more successful then either of the traditional networks. In both cases the web network was able to wipe out the opposition with little variance. The addition of the UAV allowed the web topology to accomplish the mission faster and with fewer casualties.

Each of the three scenarios demonstrate the effect of network structures on shared information. Fully connected nodes allow for more collaboration and shared awareness. According to the data communication range and accuracy are most critical to the war fighter. Each plays a significant role in mission success.

Exploring the Distribution and Flow of Information (current effort in progress)

This aspect of the work was inspired by the desire to model C2 concepts. The objective of this effort is to create an agent based model which will result in the development of a real time experiment. The model should compare the distribution and flow of information in a hierarchical, Command and Control Organization to that of a fully networked, Edge Organization.

Developed using NetLogo[10], the scenario is as follows:
Agents receive information related to a future attack. The information has been parsed into four question categories who, what, when, and where. Collectively the agents need to gather information facts to solve each of these questions. An organization will have completed its task once it answers all four questions. Each organization consists of seventeen agents and four websites. Each website is designated to convey a specific band of information. A total of sixty eight facts, seventeen for each information band will need to be distributed to the agents in order to solve the question.

In the case of the Edge Organization, each filter agent starts with at least one fact. Four selected agents start with an additional fact, representing agents with pre-attained knowledge or expertise. All facts are randomly assigned. Once play begins, additional facts are distributed in waves. The timing between fact distributions can be controlled using a slider on the program's interface. Distribution occurs when seventeen facts are randomly placed on the playing field. Each fact then moves to the closest filter. This method of distribution disburses the facts within the community at random. Factoid distribution will continue in waves until all sixty eight facts have been disbursed.

In the C2 Organization, one agent is given the position of overall coordinator. Each of the remaining sixteen filter agents is assigned to a team of four. One team member from each group of four is the team leader. Each team is tasked to work on only one band of information. Each agent starts with one fact. The overall coordinator is given a random fact. Each team member is given a fact in the information band related to their respective task. Each of the four team leaders start with an additional fact related to their information band. It is important to note that in the C2 Organization, filter agents can only interact with their team and therefore agents will only receive facts related to their team's task or information band. The overall coordinator oversees the four teams and can view all facts that have been posted to a team's website.

Once receiving information agents in both organizations can choose to share a fact with another agent or post a fact to its corresponding website. Agents check the websites and gain knowledge by updating the list of facts they have seen. It is through these methods of communication that agents achieve shared awareness and collaborate to accomplish a mission. Our goal is to measure success by investigating how long it takes for an organization to gather information and how knowledgeable each agent is at the time the organization is able to identify an answer.

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[10] Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

In running the current scenario (setup as described above), preliminary results show that the hierarchical organization identifies the four part answer faster than the edge organization. We can conclude that some organizational structure is better than none at all. However, this hierarchical structure does not deliver an optimal NCO solution. The agents only work on the task their team is assigned and do not collaborate with the group as a whole. Therefore the agents in the hierarchical model are not knowledgeable about the remaining three task questions. In contrast, the agents in the edge organization gain fairly high levels of information about all tasks through their collaboration.

Additional work will investigate the trade off of time for greater shared information and knowledge. Our team plans to take a closer look at information sharing as we further develop the scenario. By varying an agent's propensity to share/post information, we can address agent properties such as information hoarding. Keeping information from other agents could be detrimental to and organization's mission success. While information sharing is important, the rate which agents gather or pull information plays a critical role in the organizations effectiveness as well. In conducting a detailed investigation of these agent parameters, we will better represent human actions. Our results will more closely reflect each organization's capabilities.

Modeling this experiment has sparked interest within the C2 community. Many ideas have been generated for project expansion. Elements for future incorporation/investigation include:

- Recording how many actions (sharing and posting) each filter agent completes. This will determine if there are any agents hoarding information in the group.
- Introducing a deceptive fact into the set of sixty eight facts.
- Randomizing the fact distribution so that any number and combination of facts could be introduced over different time intervals.
- As specified in the real time experiment, assign point values to the facts, symbolizing key, supportive, and extraneous information.
- Investigate facts that may hold information pertaining to two bands of information. Example: Group d prefers to operate in daylight.